IEC 62047-12

Edition 1.0 2011-09

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Semiconductor devices – Micro-electromechanical devices – Part 12: Bending fatigue testing method of thin film materials using resonant vibration of MEMS structures

Dispositifs à semiconducteurs – Dispositifs microélectromécaniques – Partie 12: Méthode d'essai de fatigue en flexion des matériaux en couche mince utilisant les vibrations à la résonance des structures à systèmes microélectromécaniques (MEMS)

IEC 62047-12:2011

IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland
Email: inmail@iec.ch
Web: www.iec.ch

IEC 62047-12

Edition 1.0 2011-09

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Semiconductor devices – Micro-electromechanical devices – Part 12: Bending fatigue testing method of thin film materials using resonant vibration of MEMS structures

Dispositifs à semiconducteurs – Dispositifs microélectromécaniques – Partie 12: Méthode d'essai de fatigue en flexion des matériaux en couche mince utilisant les vibrations à la résonance des structures à systèmes microélectromécaniques (MEMS)

INTERNATIONAL ELECTROTECHNICAL COMMISSION

COMMISSION ELECTROTECHNIQUE INTERNATIONALE

PRICE CODE
CODE PRIX U

ICS 31.080.99

ISBN 978-2-88912-689-7

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

SEMICONDUCTOR DEVICES – MICRO-ELECTROMECHANICAL DEVICES –

Part 12: Bending fatigue testing method of thin film materials using resonant vibration of MEMS structures

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 62047-12 has been prepared by subcommittee 47F: Micro-electromechanical systems, of IEC technical committee 47: Semiconductor devices.

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

FDIS	Report on voting
47F/80/FDIS	47F/90/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.

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

A list of all parts of IEC 62047 series, under the general title *Semiconductor devices – Microelectromechanical devices,* can be found on the IEC website.

The committee has 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.

SEMICONDUCTOR DEVICES – MICRO-ELECTROMECHANICAL DEVICES –

Part 12: Bending fatigue testing method of thin film materials using resonant vibration of MEMS structures

1 Scope

This part of IEC 62047 specifies a method for bending fatigue testing using resonant vibration of microscale mechanical structures of MEMS (micro-electromechanical systems) and micromachines. This standard applies to vibrating structures ranging in size from 10 μm to 1 000 μm in the plane direction and from 1 μm to 100 μm in thickness, and test materials measuring under 1 mm in length, under 1 mm in width, and between 0,1 μm and 10 μm in thickness.

The main structural materials for MEMS, micromachine, etc. have special features, such as typical dimensions of a few microns, material fabrication by deposition, and test piece fabrication by means of non-mechanical machining, including photolithography. The MEMS structures often have higher fundamental resonant frequency and higher strength than macro structures. To evaluate and assure the lifetime of MEMS structures, a fatigue testing method with ultra high cycles (up to 10^{12}) loadings needs to be established. The object of the test method is to evaluate the mechanical fatigue properties of microscale materials in a short time by applying high load and high cyclic frequency bending stress using resonant vibration.

2 Normative references

The following referenced documents are indispensable for the application 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 62047-3:2006, *Semiconductor devices – Micro-electromechanical devices – Part 3: Thin film standard test piece for tensile testing*

ISO 12107, *Metallic materials – Fatigue testing – Statistical planning and analysis of data*

3 Terms and definitions

For the purposes of this document the following terms and definitions apply

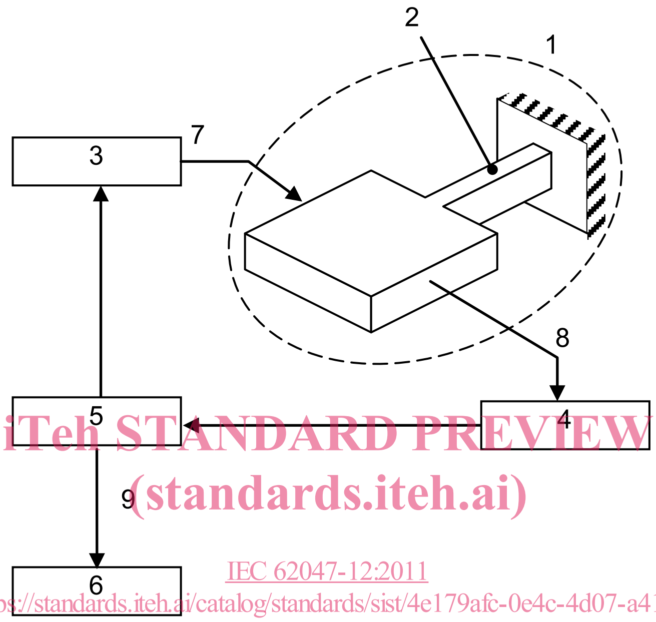
3.1
amplitude
one-half the algebraic difference between the maximum value and minimum value in a loading cycle

3.2
load ratio
algebraic ratio of the maximum value and minimum value of the load of a cycle

3.3
S-N curve
plot of stress or strain (S) against the number of cycles (N) to failure

3.4
reference strength:
static strength or instantaneous failure strength

3.5
instantaneous failure strength
failure strength of quasi-static test or resonant vibration test at rapid amplitude growth



IEC 2064/11

Key

1 Specimen
2 Test part
3 Actuator
4 Sensor
5 Controller
6 Recorder
7 Force
8 Displacement or strain
9 Amplitude and frequency

Figure 1 – Block diagram of the test method

4 Test equipment

4.1 General

The test equipment shall be capable of generating resonant vibration with constant amplitude and stable frequency to the test structure. A block diagram of the test equipment is shown in Figure 1. The test equipment consists of an actuator for oscillation, a sensor for amplitude detection, a controller for maintaining the resonant vibration at a constant amplitude, and a recorder for monitoring.

The amplitude control method is classified as follows.

a) Constant strain control

Applied strain in the test part is maintained at constant. It can be applied for elastic or inductile materials.

b) Constant stress control

Applied stress in the test part is maintained at constant. Load monitoring and closed loop control is crucial for the method.

4.2 Actuator

The actuator shall be capable of applying oscillation force of the necessary amplitude and frequencies along the required direction. Various kind of actuators can be used, e.g., electrostatic, piezoelectric, thermal, and electromagnetic actuators. The actuator may be installed in the test structure, as discussed in 5.1.

4.3 Sensor

The sensor shall be capable of measuring the movement of the specimen to determine the stress amplitude (for constant stress amplitude testing) or the strain amplitude (for constant strain amplitude testing) to the test part of the specimen.

The sensor and its associated electronics shall be accurate to within 1 % of the range of the stress or strain amplitude.

The sensor should measure the movement continuously, in order to maintain a constant vibration and detect failure effectively. If the specimen is an elastic material and will not show the change in the vibrating properties, however, it is permissible to measure the movement at regular time intervals.

The movement is detected by measuring displacement of the test structure or the stress or strain in the test structure. Clause A.2 shows a method for detecting rotational displacement of the mass from changes in capacitance. Clause B.2 shows a method using a strain gauge integrated in the specimen. Clause C.2 shows a method for detecting displacement of the mass using a non-contact displacement gauge.

4.4 Controller

The controller shall be capable of generating the oscillation signal to the actuator from the movement signal from the sensor, in order to maintain the required resonant vibration. During testing, the amplitude and frequency of the specimen shall be maintained at a constant level. One of the following methods should be applied for the specimen, depending on the vibration characteristics.

a) Closed loop method

The frequency and amplitude of the oscillation signal applied to the specimen shall be controlled to follow changes in the resonant frequency. In most cases, the signal applied to the actuator is generated from the movement signal of the specimen. A self-excited oscillation circuit or phase-locked loop circuit can be used as a means for maintaining the resonant frequency. An automatic gain control circuit (AGC) can also be used to maintain a constant amplitude by changing the amplitude of the oscillation signal based on the detected amplitude.

b) Open loop method

Elastic or inductile materials that show a linear response but no plastic deformation may be tested using an open loop method. This test may be performed by stopping at regular intervals and measuring the resonant characteristics, or by actuating the test structure from the start to the end of testing at a predetermined resonance frequency and oscillation signal amplitude.

The stability of the frequency and amplitude shall be maintained throughout the test to within ± 3 % of the desired value.

4.5 Recorder

The test equipment shall include a recorder for collecting the “record data” indicated in 8.6.

4.6 Parallel testing

The test may be conducted in parallel with a number of equipment units. In this case, steps should be taken to eliminate mutual electrical or mechanical interference among the equipment units.

5 Specimen

5.1 General

The specimen shall be capable of applying a constant and high-load amplitude to the test part via resonant vibration. Examples of specific structures are shown in the Clauses A.1, B.1, and C.1.

It is permissible to integrate a mechanism in the specimen for actuating or for sensing the movement of the specimen. An example of a structure integrating mechanisms for actuation and detecting amplitude is shown in Annex A.1. An example of a structure integrating a mechanism for detecting amplitude only is shown in Annex B.1.

5.2 Resonant properties

The specimen shall have resonance characteristics that enable the application of the required deformation (mode of vibration) in the specific frequency (resonance frequency) of the specimen. The resonant frequency should preferably be more than 1 000 Hz, in order to obtain a large number of the cycles in a short time. The quality factor of the specimen should be more than 100, in order to obtain a large amplitude. Steps should be taken to ensure, within this resonance frequency, that the specimen will not vibrate in a vibration mode different from that used in the test. For example, there should be no other resonant modes close to the mode used for testing.

5.3 Test part

The specimen shall have a test part in which stress sufficient to induce failure occurs. When the test is performed to evaluate the reliability of the actual device, the deformation in the test part at resonant vibration (in-plane and out-of-plane bending) shall be the same as that of the actual device. If only low stress can be applied to a structure similar to the actual device, a notch or another means may be introduced to concentrate the stress in the targeted section of the test part.

5.4 Specimen fabrication

Refer to Clause 5 of IEC 62047-3 when manufacturing the test part of the specimen. The specimen should be fabricated by the same method as the target MEMS device for reliability evaluation is fabricated. Furthermore, the same shapes, dimensions, and multilayer film structures should be used.

6 Test conditions

6.1 Test amplitude

The test amplitude should be specified from the appropriate reference strength of the specimen. The reference strength should be determined through the methods in 7.1. One of the following procedures should be chosen for determining the test amplitude during testing, based on the reference strength.

a) Constant amplitude of 100 % of the reference strength:

   to evaluate the fatigue life at a certain amplitude.

b) Decrease the amplitude gradually from a high level:

   for obtaining an S-N curve in a short time.

c) Increase the amplitude gradually from a low level:

   for obtaining an S-N curve when the number of test parts is limited.

As a reference for determining the test amplitude, example of experimental data and analysis of fatigue testing for silicon are shown in Annex D. For details on the testing of metal materials, refer to ISO 12107.

The decrease and increase step of the test amplitude for the procedures b) and c) should be selected preferably close to the standard deviation of measured reference strength.

6.2 Load ratio

The load ratio of the test method can be taken to be -1, as the quality factor (*Q*) of the resonant vibration is high enough (10 or more) to achieve an amplitude too high to apply by (quasi-)static testing methods.

6.3 Vibration frequency

The frequency shall be the resonant mode at which the test part is in the required stress state specified in 5.3, or a frequency close to it.

6.4 Waveform

The waveform of the displacement of the specimen and the stress and strain of the test part can be regarded as sinusoidal, irrespective of the actuating waveform.

6.5 Test time

The test time shall be specified as the time at which the test ends, even if the specimen has not failed by that time. The test time can be determined as the number of the test cycles, based on the vibration frequency. For tests conducted on materials with lifetime characteristics which are frequency-independent, such as silicon, the test cycles are chosen as the stress cycles applied on the actual devices in their lifetimes. See Annex D.

6.6 Test environment

The test environment should be maintained at a constant temperature and humidity.

7 Initial measurement

7.1 Reference strength measurement

The reference strength shall be measured prior to the fatigue test. Specimens used for measurement of the reference strength should be made of the same materials, and by the same processes, as the test part to be tested. Care shall be taken when using a specimen of a different shape. If such a specimen is used, it should show the same failure mode, and the size effect on the measured strength should be considered.

The reference strength should be determined using one of the following tests.

a) Quasi-static test

The failure strength measured by conducting quasi-static testing is set as the reference strength.

b) Instantaneous fatigue test

The maximum amplitude in the instantaneous fatigue test is set as the reference strength. In this test, the amplitude is rapidly increased up to the point of specimen failure by the same method used for the fatigue test. This method may be chosen when it is difficult to use a specimen of a different shape, or when it is difficult to apply a static load.

c) Stress analysis

The reference strength is determined using either simulation or theoretical analysis. This method can be chosen when a reference strength is difficult to determine experimentally. The amplitude at which the maximum stress in the specimen reaches the failure strength is set as the reference strength. The failure strength can be taken from published papers or other available data. The reported strength should be chosen carefully, as some materials have size effect in failure strength and environmental effects under variable temperatures, humidity levels, and so on. It is thus desirable to refer to the strength values in the literature in order to keep conditions as close as possible to those in the life test to be conducted.

Given the large variation in the strength of brittle materials such as single crystal silicon, it is preferable to obtain strength data for no less than 10 specimens when measuring the reference strength experimentally, and to adopt a statistically processed value (for example, 50 % failure stress from Weibull analysis or an arithmetical average) as the reference for stress or strain in the resonant oscillation test.

7.2 Frequency response test

The resonant properties of the specimens shall be measured prior to the fatigue test. When the resonant properties vary among specimens and the controller needs tuning, the resonant properties of all of the specimens should be measured.

The frequency response test is used to measure the resonant properties. The oscillation signal is applied from a function generator and the frequency of the signal is swept around the expected resonant properties to find the actual resonant frequency. The load applied in this response test shall be small enough to ensure that the measurements for the fatigue test are unaffected. If the effect cannot be ignored, the number of load cycles applied in this response test should preferably be added to the fatigue test data.

8 Test

8.1 General

The fatigue test shall be conducted by applying resonant oscillation at the predetermined oscillation amplitude to the specimen. The test ends when the specimen fails or the predetermined test time is reached.

8.2 Initial load application

The increasing rate of the amplitude should be specified properly at the start of the fatigue test. Because the test is conducted in resonance and the quality factor is high, the amplitude cannot reach the test amplitude without delay. If the amplitude increases too rapidly, it can result in an overshooting of the amplitude and unexpected failure at the start of the test. If, on the other hand, too much time is allowed for the increase in amplitude, the test result can be affected. The initial load applied in these procedures should be carefully controlled to ensure that measurement results of the lifetime test are unaffected. When some effect is conceivable, the procedures for increasing the amplitude should be described in the test report.

8.3 Monitoring

The vibration of the specimen shall be monitored continuously during the test to detect the specimen failure. One method for this test monitoring is to monitor the vibration frequency and/or amplitude. It is also desirable to record the changes in the vibration frequency and amplitude at proper time intervals. If the system lacks a monitoring function, the specimen may be monitored by stopping the fatigue test at certain intervals of time and conducting the frequency response test in 7.2.

8.4 Counting the number of cycles

The number of cycles of the fatigue test shall be counted using a counter. Alternatively, the cycles may be calculated by multiplying the vibration frequency by the time from the start of testing.

8.5 End of the test

The test shall end at the point of specimen failure, or when a predetermined loading time or a predetermined number of cycles has elapsed.

Specimen failure is defined as the following:

a) fracture of the test part;
b) a certain percentage change in the amplitude;
c) a certain change in the oscillating frequency.

8.6 Recorded data

The failure of the specimen shall be recorded. The oscillation amplitude and frequency of the specimen and the temperature and humidity of the testing environment should be measured at certain intervals of time during the test.

9 Test report

The test report shall include the following information.

- Mandatory

  a) reference to this International Standard, i.e. IEC 62047-12
  b) test piece material
     – in the case of a single crystal: crystallographic orientation
  c) method and details of test piece fabrication
     – method of thin film deposition
     – fabrication processes
     – heat treatment (annealing) conditions
  d) shape and dimensions of test piece
  e) test equipment
     – oscillation method (self-oscillation, external oscillation)
     – initial load application method
     – amplitude control method
     – test monitoring method (amplitude, frequency, number)

f) fatigue test conditions
   - reference strength, and its measurement method
   - mean stress (in the case of displacement control, mean displacement)
   - stress amplitude (in the case of displacement control, displacement amplitude)
   - load ratio
   - testing environment (temperature and relative humidity)
   - wave form (sinusoidal)
   - frequency

g) fatigue test result
   - number of samples
   - number of applied cycles to failure. If the test piece is not fractured during a predetermined number of cycles, the number of cycles and the description "no failure" should be noted.
   - definition (type) of failure

- Optional

a) purpose of the test
   - motivation or object

b) microstructure
   - in the case of polycrystalline thin film: texture and grain size

c) internal stress

d) mask design
   - resolution of mask drawing and lithography

e) surface roughness of test piece
   - photographs of the finished test part, along with any surface treatment (cleaning procedure)

f) brief description of fracture characteristics

g) detailed test results
   - S-N curve (S is peak stress or stress amplitude)
   - fatigue strength, statistical processing (fatigue probability)
   - amplitude history
   - fractograph.