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INTERNATIONAL STANDARD

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Semiconductor devices – Micro-electromechanical devices – Part 32: Test method for the nonlinear vibration of MEMS resonators

Dispositifs à semiconducteurs – Dispositifs microélectromécaniques – Partie 32: Méthode d’essai pour la vibration non linéaire des résonateurs MEMS

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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
47F/322/FDIS	47F/325/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

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SEMICONDUCTOR DEVICES –
MICRO-ELECTROMECHANICAL DEVICES –

Part 32: Test method for the nonlinear vibration of MEMS resonators

1 Scope

This part of IEC 62047 specifies the test method and test condition for the nonlinear vibration of MEMS resonators. The statements made in this document apply to the development and manufacture for MEMS resonators.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 62047-1, *Semiconductor devices – Micro-electromechanical devices – Part 1: Terms and definitions*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 62047-1 and the following apply.

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
nonlinear vibration
vibration whose displacement has a nonlinear relationship with the elastic restoring force, with the change of the vibration amplitude

3.2
nonlinear jump
jump phenomenon of the frequency response curve when the vibration amplitude exceeds a certain threshold

3.3
frequency deviation
deviation of the vibration frequency of the resonator in a closed-loop system from the natural frequency of the resonator

4 Test parameters of nonlinear vibration of the resonators

Test parameters of nonlinear vibration of the resonators are:

a) amplitude-frequency response of the nonlinear vibration, $A(\omega)$;

b) phase-frequency response of the nonlinear vibration, $P(\omega)$;

c) bending factor of the amplitude-frequency response, b;

d) amplitude threshold for the nonlinear jump, a_c;

e) frequency deviation of the self-exciting closed-loop system, E_1;

f) frequency deviation of the phase-locked closed-loop system, E_2;

g) frequency deviation of the burst-exciting closed-loop system, E_3.

5 Test method for the amplitude-frequency response and phase-frequency response of the nonlinear vibration

5.1 Test system

A test system consists of the following equipments:

a) laser vibrometer;
b) micro-optical apparatus;
c) signal generator;
d) vacuum chamber;
e) mounting fixture;
f) vacuum pump;
g) angle valve.

The test system is illustrated in Figure 1.

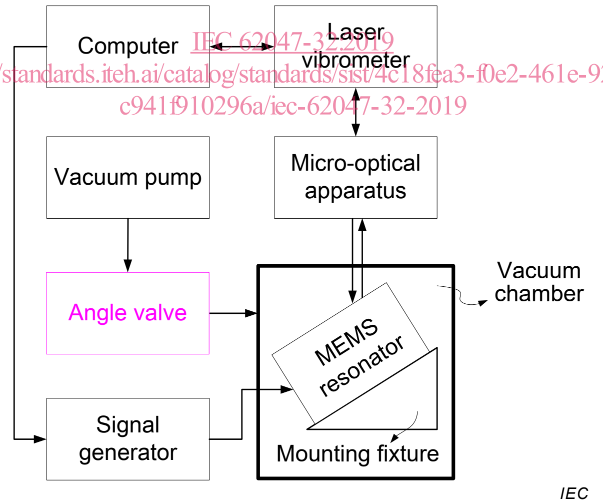

Figure 1 – Test system

5.2 Test conditions

a) Keep the ambient temperature within 23 °C ± 5 °C.

b) Maintain the vacuum degree of the vacuum chamber according to the actual operation of the resonator.

c) Adjust the micro-optical apparatus to restrict the laser spot within the surface of the resonator.

d) For transparent resonators, the laser beam should illuminate on the metal layer on the resonator to enhance the reflected laser intensity.

e) The connection of the resonator, the installing base and the vacuum chamber should be strong enough.

f) For out-of-plane vibrating resonators, the surface of the installing base should be parallel to the horizontal plane. For in-plane vibrating resonators, the surface of the installing base should be set to a certain angle about the horizon level, to ensure enough intensity of the reflected laser into the detector.

g) The vacuum pump and the vacuum chamber should be connected with flexible bellows in case of the vibration propagation from the pump to the chamber.

h) The angle valve should be tightly shut off to well maintain the vacuum level, and then the pump turned off before operating the test procedure.

5.3 Test procedures

a) Set the frequency of the vibration excitation according to the estimated value of the natural frequency of the resonator. And then implement the initial frequency scan around the natural frequency within a wide range. The amplitude frequency response and the phase frequency response can be measured according to the vibration displacement of the resonators. And record the resonant frequency of the resonator.

b) Reset the vibration excitation parameters to implement the frequency scan for the second time: reducing the interval of the frequency scan to half of that set in the initial frequency scan and reducing the range of the frequency scan to ten times of the half-power bandwidth of the amplitude frequency response. The amplitude frequency response and the phase frequency response can be measured according to the vibration displacement of the resonators. And record the resonant frequency of the resonator.

c) Compare the resonant frequencies obtained by the initial and the second tests. If the discrepancy in the resonant frequencies is smaller than 1 ppm[1] of the resonant frequency measured in the second test, either the initial or the second test result can be deemed as the accurate amplitude frequency response and the phase frequency response. If the discrepancy in the resonant frequencies exceeds 1 ppm of the resonant frequency measured in the second test, the third time frequency scan with further small frequency interval should be implemented, until the discrepancy in last tested resonant frequency and the previous one is smaller than that 1 ppm of the resonant frequency measured in the last test.

6 Test method for the bending factor of the nonlinear vibrating frequency response

a) Test the nonlinear vibrating amplitude frequency response of the MEMS resonator according to the method presented in Clause 5. And obtain the resonant frequency ω_r and the resonant amplitude a_r.

b) The bending factor can be calculated by substituting the resonant frequency ω_r and the resonant amplitude a_r into Formula (A.11) as provided in Annex A. The value of ω_n can be determined by its design value.

$$b = \frac{\omega_r - \omega_n}{a_r^2} \tag{1}$$

7 Test method for the amplitude threshold for the nonlinear jump

a) Obtain the bending factor of the amplitude frequency response of the MEMS resonator by the method set out in Clause 6.

b) The nonlinear jump phenomenon is presented in Annex B. Figure B.1. The amplitude threshold for the nonlinear jump can be calculated by substituting the bending factor b into Formula (2).

1 ppm = part per million

$$a_c = \sqrt{\frac{4\omega_n}{3\sqrt{3}Q|b|}} \tag{2}$$

where

a_c is the amplitude threshold for the nonlinear jump;

Q is the quality factor of the resonator with linear vibration.

The value of Q can be obtained by the following formula:

$$Q = \frac{\omega_n}{\omega_2 - \omega_1} \tag{3}$$

where

ω_1 and ω_2 are the boundary points of the -3 dB bandwidth of the linear amplitude-frequency response, which is shown in Figure 2.

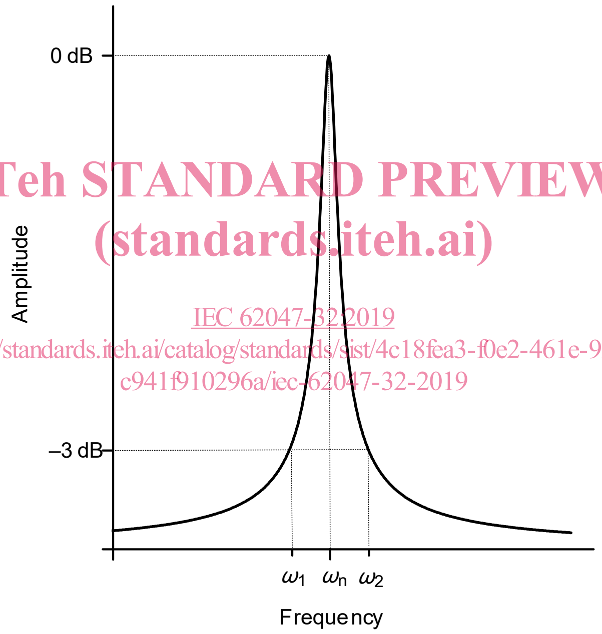

Figure 2 – 3 dB bandwidth of the linear amplitude-frequency response

8 Test method for the frequency deviation as a result of the nonlinear vibration

8.1 Frequency deviation of the self-excitation closed-loop system

a) Obtain the bending factor of the amplitude frequency response of the MEMS resonator by the method provided in Clause 6.

b) Frequency deviation of the self-excitation closed-loop system can be calculated by substituting the bending factor b into Formula (C.3).

$$E_1 = \frac{ba_s^2}{\omega_n} \times 100\ \% \tag{4}$$

8.2 Frequency deviation of the phase-locked closed-loop system

a) Obtain the bending factor of the amplitude frequency response of the MEMS resonator by the method provided in Clause 6.

b) Frequency deviation of the phase-locked closed-loop system can be calculated by substituting the bending factor b into Formula (C.12).

$$E_2 = \frac{b a_{\pi/2}^2}{\omega_\mathrm{n}} \times 100\ \% \tag{5}$$

8.3 Frequency deviation of the burst-excited system

a) Obtain the bending factor of the amplitude frequency response of the MEMS resonator by the method provided in Clause 6.

b) Frequency deviation of the burst-excited system can be calculated by substituting the bending factor b into Formula (6)

$$E_2 = \frac{b a^2}{\omega_n} e^{-\frac{1}{Q}\omega_\mathrm{n} t} \tag{6}$$

where

t is the time with the definition of $t = 0$ when disconnecting the excitation;

e is the natural constant.

Annex A
(normative)

Model of nonlinear vibration of MEMS resonators and bending factor

A.1 Model of nonlinear vibration of MEMS resonators

The vibration behaviour of the MEMS resonators can be illustrated by the Duffing equation which is shown in Formula (A.1)

$$m\ddot{x}+c\dot{x}+k_1x+k_3x^3=F^*\cos(\omega t) \tag{A.1}$$

where

m is the equivalent mass of the resonator;

c is the coefficient of the damping;

k_1 is the linear stiffness coefficient;

k_3 is the nonlinear stiffness coefficient;

F^* is the amplitude of the driving force;

ω is the frequency of the driving force;

x is the vibration displacement;

t is the time.

Then transform Formula (A.1) by dividing it by the equivalent mass, m:

$$\ddot{x}+\omega_n^2x=-\frac{c}{m}\dot{x}-\frac{k_3}{m}x^3+\frac{F^*}{m}\cos(\omega t) \tag{A.2}$$

For an actual resonator, the nonlinear term $-k_3x^3/m$ in Formula (A.2) is small. Therefore a small parameter ε is introduced to implement the multiple scales algorithm. Formula (A.2) is transformed to:

$$\ddot{x}+\omega_n^2x=-2\varepsilon\mu\dot{x}-\varepsilon\alpha x^3+F\cos(\omega t) \tag{A.3}$$

where

$$\alpha=\frac{k_3}{m\varepsilon} \tag{A.4}$$

$$\mu=\frac{c}{2m\varepsilon} \tag{A.5}$$

$$F=\frac{F^*}{m} \tag{A.6}$$

A.2 Solution of the nonlinear vibration model

The solution of the nonlinear vibration model is derived by the multiple scales algorithm, which is shown in Formula (A.7).

$$x = a\cos\left(\omega t - \varphi\right) + \mathrm{O}\left(\varepsilon\right) \tag{A.7}$$

where

a is the vibration amplitude of the MEMS resonators;

φ is the phase delay between the vibration displacement of the MEMS resonator and the force;

$\mathrm{O}\left(\varepsilon\right)$ is the symbol of the same order infinitesimal of ε.

The amplitude-frequency response of the MEMS resonator is shown in Formula (A.8) in an implicit expression.

$$\omega = \omega_\mathrm{n} + ba^2 \pm \sqrt{\frac{F^2}{4\omega_\mathrm{n}^2 a^2} - \varepsilon^2\mu^2} \tag{A.8}$$

where

$$b = \frac{3\alpha\varepsilon}{8\omega_\mathrm{n}} \tag{A.9}$$

The phase-frequency response of the MEMS resonator is shown in Formula (A.10) in an implicit expression.

$$\omega = \omega_\mathrm{n} + b\frac{F^2}{4\varepsilon^2\omega_\mathrm{n}^2\mu^2}\sin^2\varphi - \mu\varepsilon\cot\varphi \tag{A.10}$$

A.3 Bending factor of the amplitude-frequency response

The nonlinear amplitude-frequency response of the MEMS resonator can be derived from Formula (A.8), which is shown in Figure A.1. The curve between the left and the right branches is the bone curve.