Development and evaluation status of "Twin"-TQCM for deep cryogenic environment down to 40K

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NASA Goddard Space Flight Center

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Purpose of development

To contribute to all space activities, characterize

i . the external contamination environment

ii . the background in-flight contamination outgassing environment caused by flyby and landed missions

iii . the background water off-gassing environment for lunar water detection
➡ Temperature is less than 40K at “permanently shadowed regions”

iv . the level of outgassing in the cryogenic science instrument like Optical Telescopes

v . the molecular outgassing environment inside launch vehicle fairings

vi . the influence of AO

Concept of “NEW” product

Making QCM users happier !

幸せ

- **S**mart
- **H**ighest quality
- **I**nnovative
- **A**daptable
- **W**orld new standard
- **A**ffordable (Cost effective)
- **S**mall & light
- **E**ssential

Development history and future plan

Jul. 2015 : NDK and JAXA have started development.

Jan. 2017 : Development of Twin-CQCM Sensor Module & Controller have been completed.

Jul. 2018 : Development of Twin-TQCM Sensor Module & Controller have been completed.

Twin-QCM

Jul. 2019 : Started overseas sales (Support CE Marking).

Controller for 4 QCMs

Nov. 2021:Started development of "Flight Systems".

Mar. 2025:Development of "Prototype Flight Model" will be completed.

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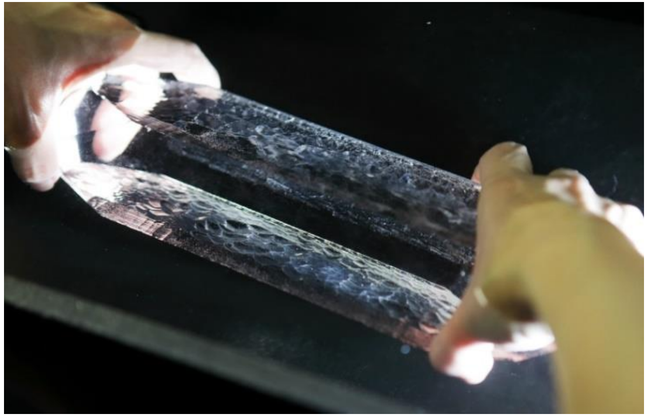
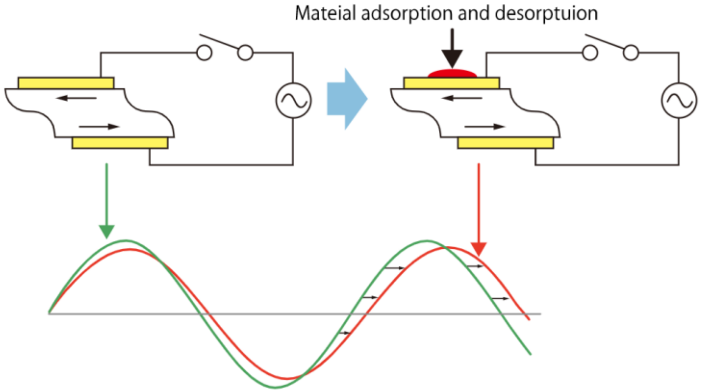
Measurement principle of QCM

Crystal devices are electronic components that control and select frequencies with high accuracy and stability.
When a substance attaches to the electrode of the crystal sensor surface, a frequency drop corresponding to the mass adsorbed appears(=Mass load effect), so it is also used as a sensor and is generally called as QCM sensor.

QCM: Quartz crystal microbalance





Conversion between frequency and mass can be expressed by Sauerbrey equation

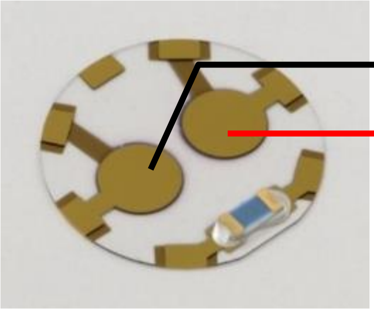
$$\left|\delta f\right| = k \times f^2 \times \delta m$$

Δm : Reacted mass(g)
δF : Frequency variation before and after reaction(Hz)
F : Nominal frequency of quartz crystal(Hz)
K : Coefficient based on each quartz crystal

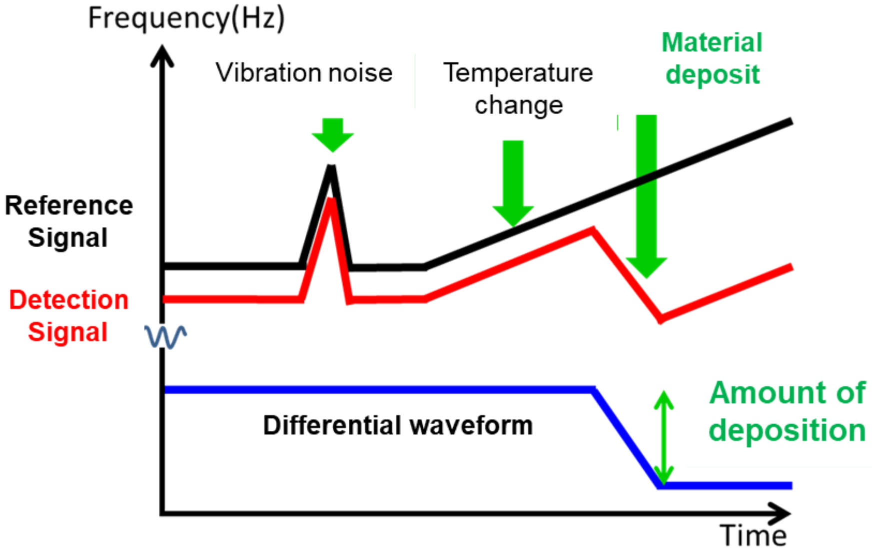
What is "Twin"-QCM ?

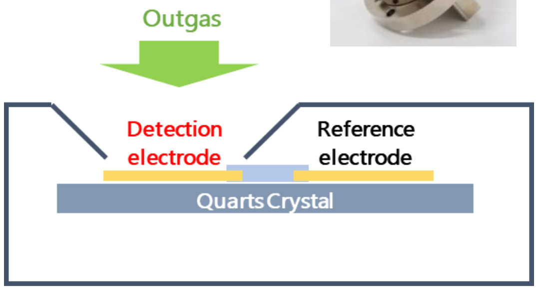
Forming 2 electrodes(Reference and Detection) on 1 crystal piece

enables to cancel the outer factors like temperature change and vibration
to keep stable and precise measurement of outgases without "Crystal matching"



"Twin"-QCM sensor
(diameter=14mm)





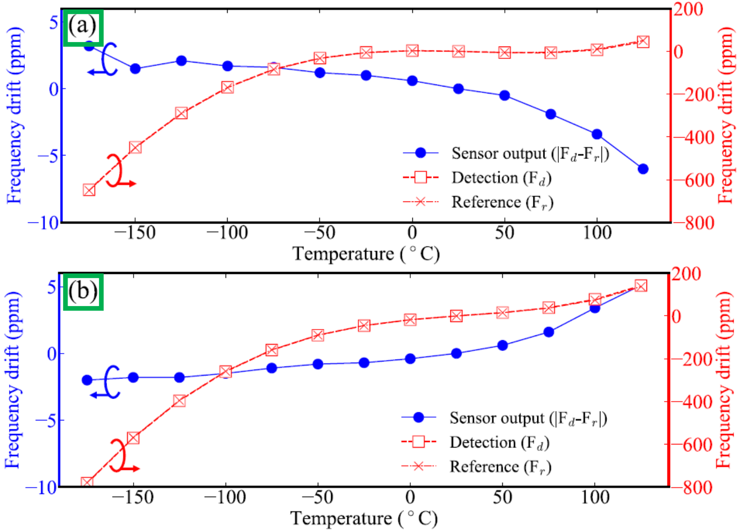
Schematic diagram of
"Twin"-QCM sensor

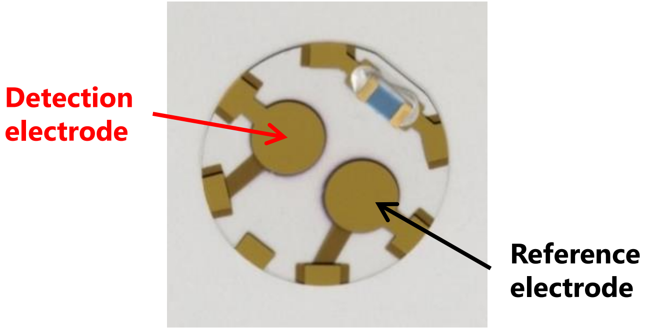
Features of “Twin”-QCM 1/2

Frequency vs. temperature characteristic (Ground model)

Performance ≦±10 ppm(-175℃ to +125℃)

Frequency drift in (a)fundamental(10MHz) and
(b)3rd overtone(30MHz) mode caused by temperature dependency.





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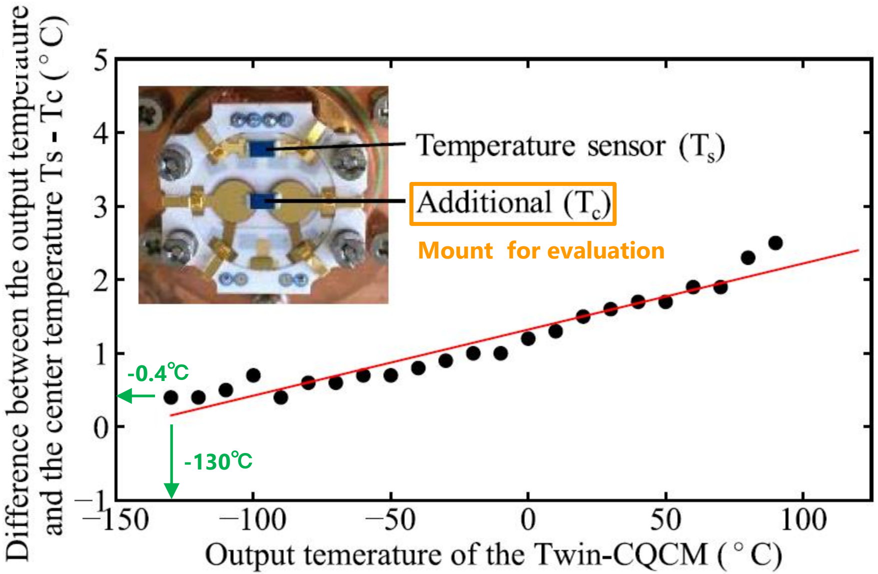
IEEE Sensors Journal.
vol. 21, no.9, pp.
10530-10538, 2021.

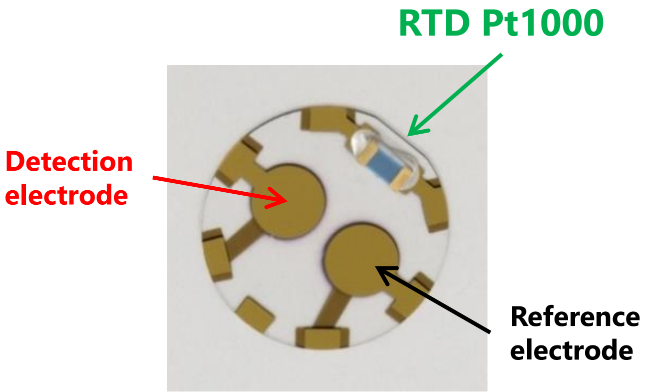
Features of "Twin"-QCM 2/2

Temperature Measurement Accuracy (Ground model)

Performance	≦2.6℃(-130℃ to +100℃)

The difference between the two RTDs was less than 2.6℃. The error was 0.4℃ at -130℃.





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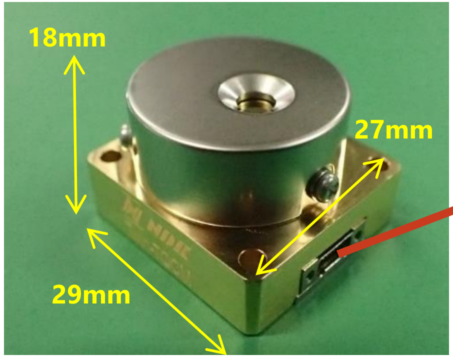
Main specifications 1/2 (preliminary)

Items		Specifications	Remarks
Number of sensor module		1～2	
Frequency measurement resolution		0.01Hz	
Measurement interval		Min. 1s	100ms is possible in case of 1 sensor module
Operating temperature range	Sensor module	-233～+125℃	
	Controller	-10～+70℃	
Temperature control range		-233～+110℃	In case temperature of base plate is -233℃
Differential frequency temperature characteristic		±10ppm	Based on +25℃
Measurement viewing angle		60° (Half Angle)	
Power supply voltage		DC+28V（DC +24～+32V）	Insulated power supply circuit
Power consumption	Continuous operation (Peak)	35W(2 Sensor modules) 25W(1 Sensor modules)	During full cooling/heating
	Intermittent operation	1.5W(2 Sensor modules) 1.3W(1 Sensor modules)	30min. operation/24hours

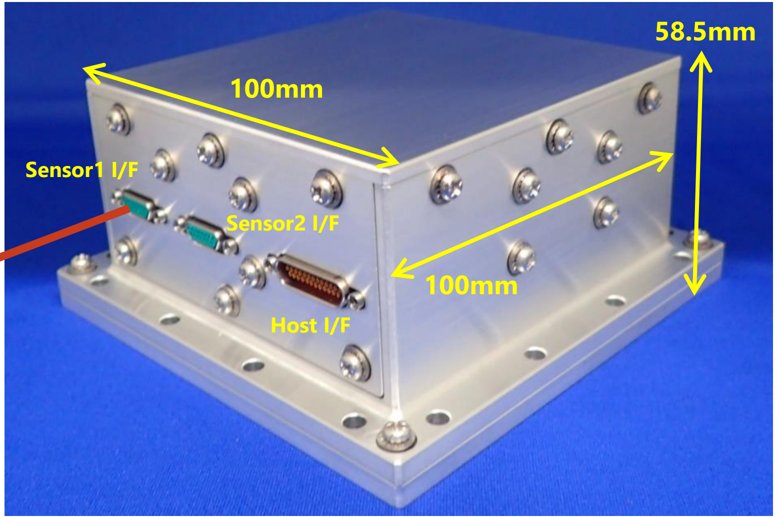
Main specifications 2/2 (preliminary)

Items		Specifications	Remarks
Controller external interface	Host I/F connector	Micro-Dsub 25pin(Socket)	
	Serial communication	RS-422(1～2ch) Full-duplex 34,800bps	
	AB(Active Bi-level) Telemetry output	1 circuit(+5V/0V output)	Host side input impedance: More than 1MΩ Output impedance: Less than 1kΩ
	PB（Passive Bi-level） Telemetry output	1 circuit(No-voltage interface output)	ON resistance: Less than1.5Ω Absolute maximum rating: ±30V, 0.2A
	Sensor module I/F connector	Micro-Dsub 15pin(Plug)×2	Max. cable length is 20m

Size & Weight (preliminary)



Connection cable



Sensor module(TQCM)

	Volume (mm^3)	Mass (g)
Ground	15,810	39.4
EM1	10,692	23.0
	-32%	-42%

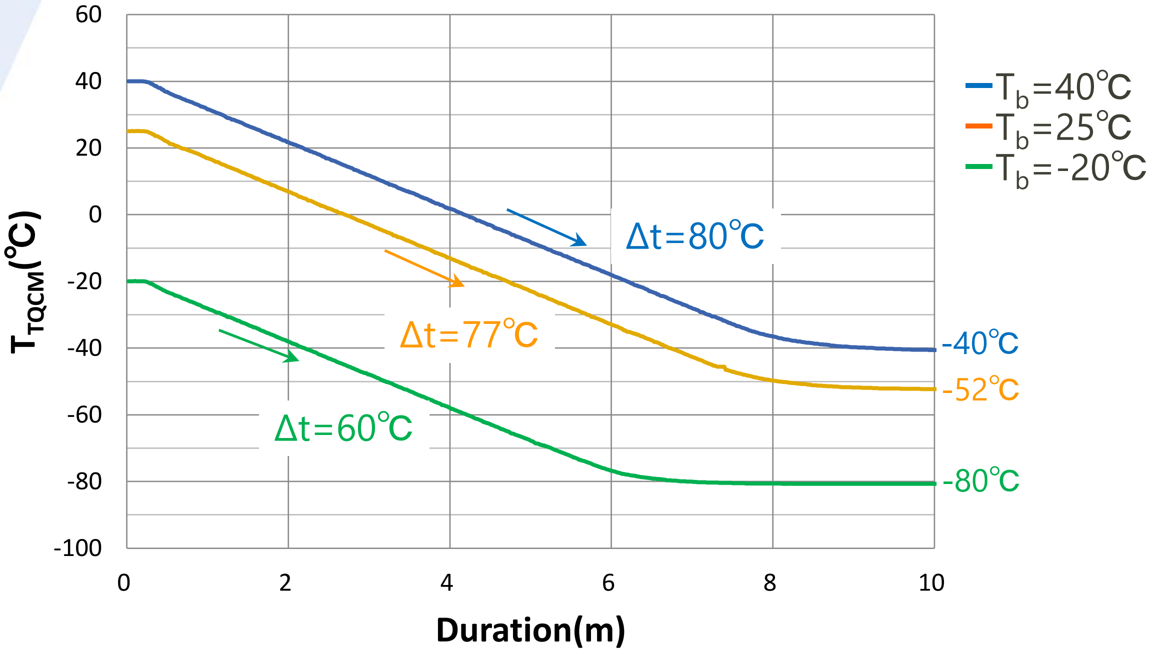
Controller for 2 Sensor modules

	Volume (mm^3)	Mass (kg)
Ground	28,784,316	<10
EM0	585,000	<1.1
	-98%	-89%

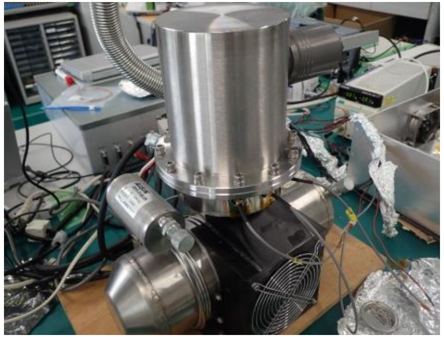
Ground: Current ground model

Twin-TQCM cooling characteristics

Using peltier element as cooling mode



*T_b : Temperature of TQCM base plate



NDK's small cryogenic chamber

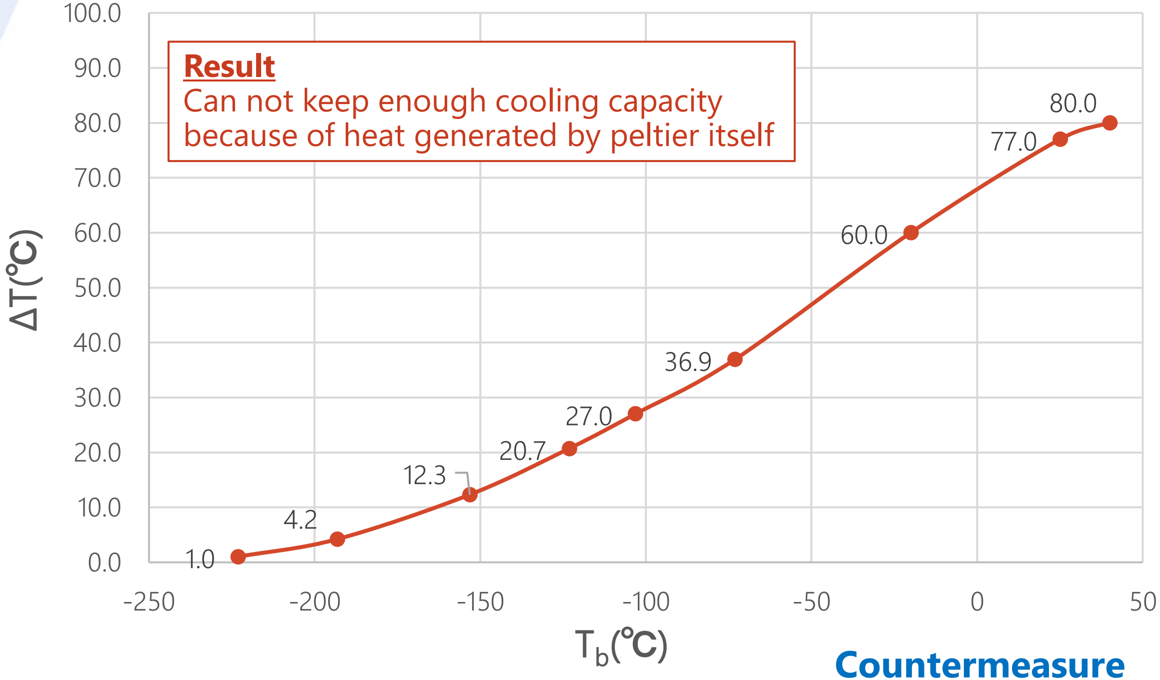
Conditions
- Use NDK's small cryogenic chamber (Lowest temperature is -223℃ at T_b)
- TQCM temperature ramp rate: 10℃/min
- Vacuum pressure: <10^{-3}Pa

Protocol
a. Set T_b to each temperature
b. Cooling with above ramp rate
c. Measure the saturated temperature

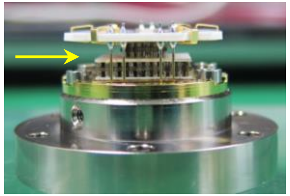
Result
Enough cooling capacity as a TQCM used for ground test

Twin-TQCM cooling characteristics

Using peltier element as cooling mode at lower temperature



Peltier element



Inside of TQCM without cover (Ground model)

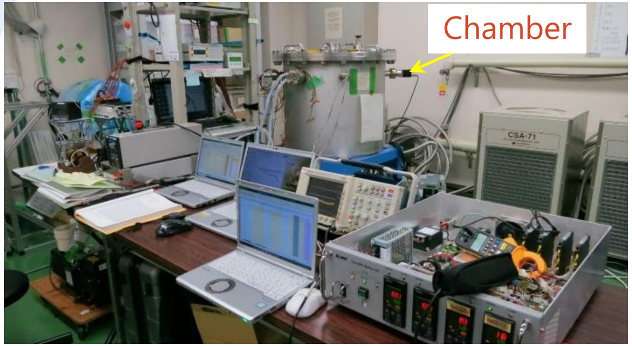
Tb(℃)	Tb(K)	⊿T(℃)
40.00	313.15	80.0
25.00	298.15	77.0
-20.00	253.15	60.0
-73.15	200.00	36.9
-103.15	170.00	27.0
-123.15	150.00	20.7
-153.15	120.00	12.3
-193.15	80.00	4.2
-223.15	50.00	1.0

Countermeasure

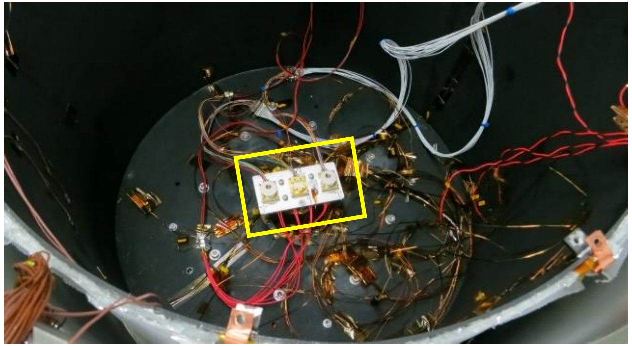
➡Use peltier as heating mode even in the cooling stage

Twin-TQCM temperature monitor

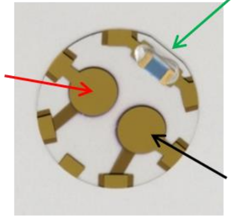
Accuracy of RTD Pt1000 as temperature monitor



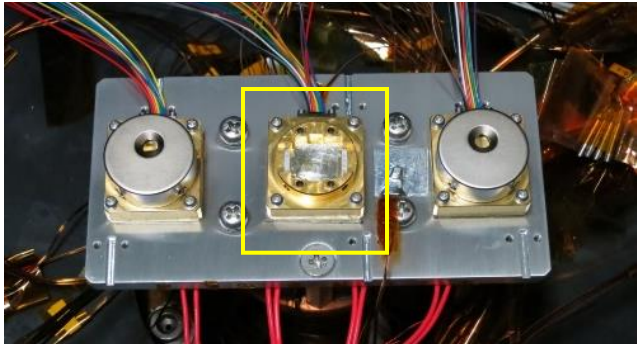
JAXA's cryogenic chamber



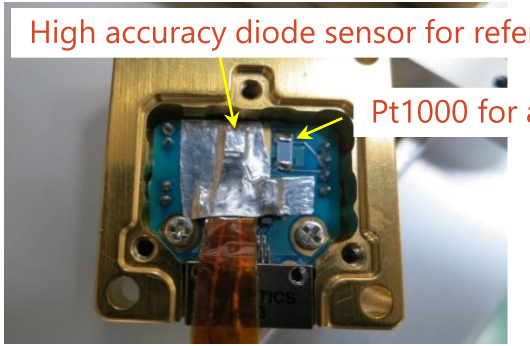
Inside of chamber



Actual installation of Pt1000 on quartz crystal



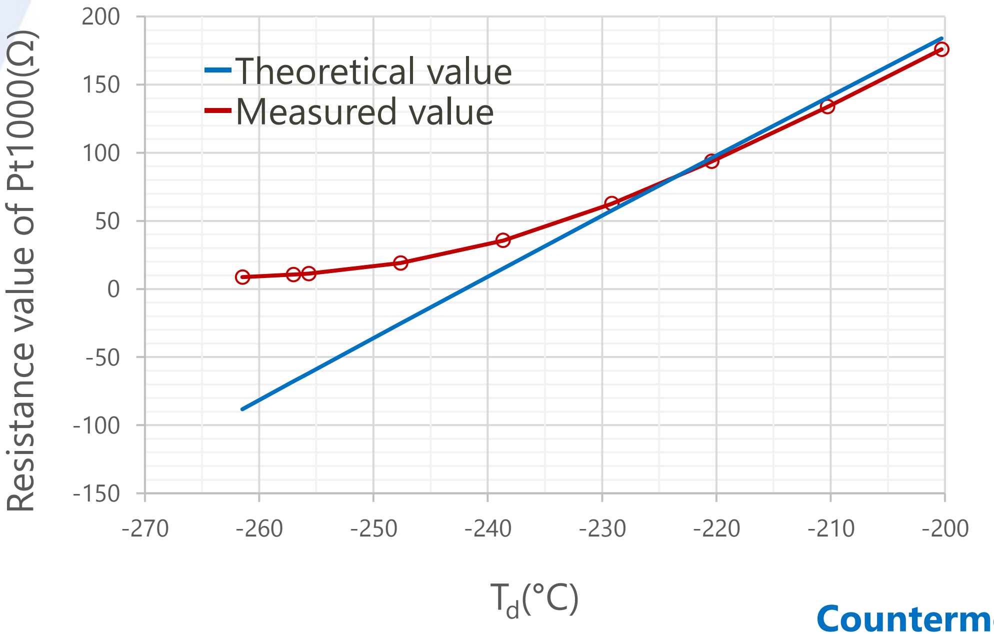
TQCM EM0s under test



Pt1000 for test

Twin-TQCM temperature monitor

Accuracy of RTD Pt1000 as temperature monitor



*T_d : Temperature of diode sensor

Conditions
・Use JAXA's cryogenic chamber
(Lowest temperature is -265℃ at T_b)
・Temperature ramp rate: 2℃/min
・ Vacuum pressure: <10^{-4}Pa

Protocol
a. Cooling with above ramp rate
b. Measure temperature of diode sensor
c. Measure resistance value of Pt1000
d. Compare and consider the result

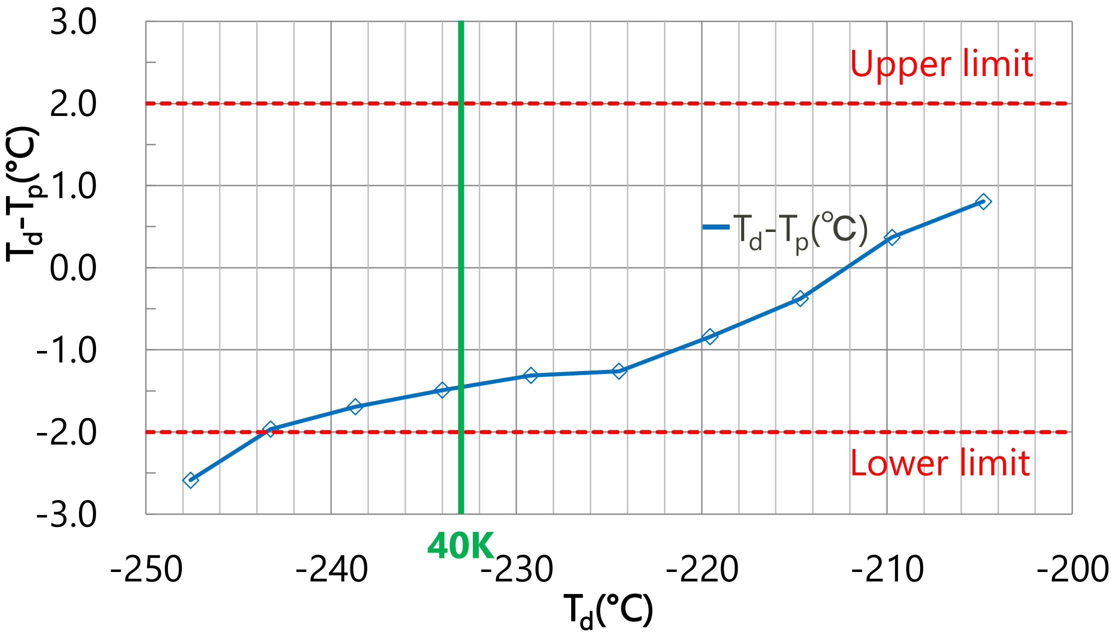
Result
In the region below -200°C, resistance value of Pt1000 did not change based on theory.
*Specified operating temperature range of Pt1000 is -200 to 850℃

Countermeasure

➡Compensate the measured value of Pt1000 by using temperature correction table to monitor and control the frequency of quartz crystal precisely

Twin-TQCM temperature monitor

Accuracy of RTD Pt1000 after applying compensation



*T_d : Temperature of diode sensor

T_p : Temperature of Pt1000

Result

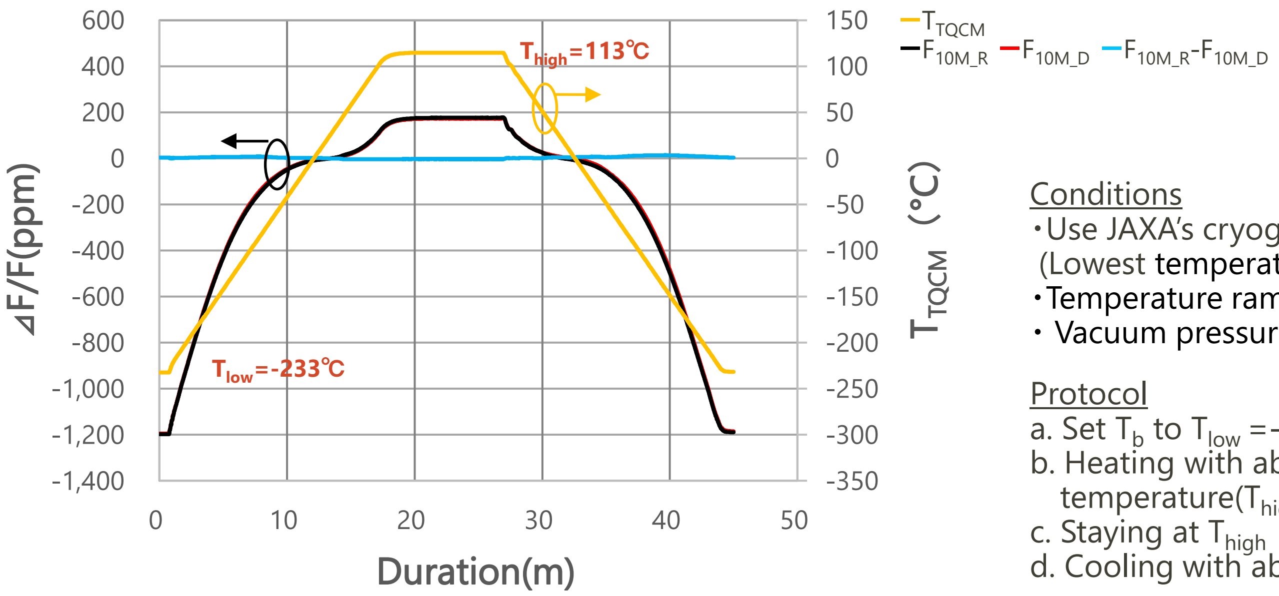
Measured error of RTD was

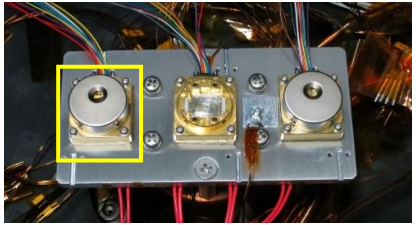
- -1.8℃ at -240℃
- -1.5℃ at -233℃(40K)

➡ Within target of ±2℃

Oscillation vs. temperature characteristics

Using updated Peltier and RTD Pt1000





TQCM EM0s under test

<u>Conditions</u>

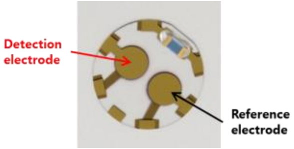
- Use JAXA's cryogenic chamber (Lowest temperature is -265℃ at T_b)
- Temperature ramp rate: 20℃/min
- Vacuum pressure: <10^{-4}Pa

<u>Protocol</u>

a. Set T_b to T_{low} =-233℃(40K)
b. Heating with above ramp rate to the highest temperature(T_{high})
c. Staying at T_{high} for 10 min
d. Cooling with above ramp rate to T_{low}

<u>Result</u>

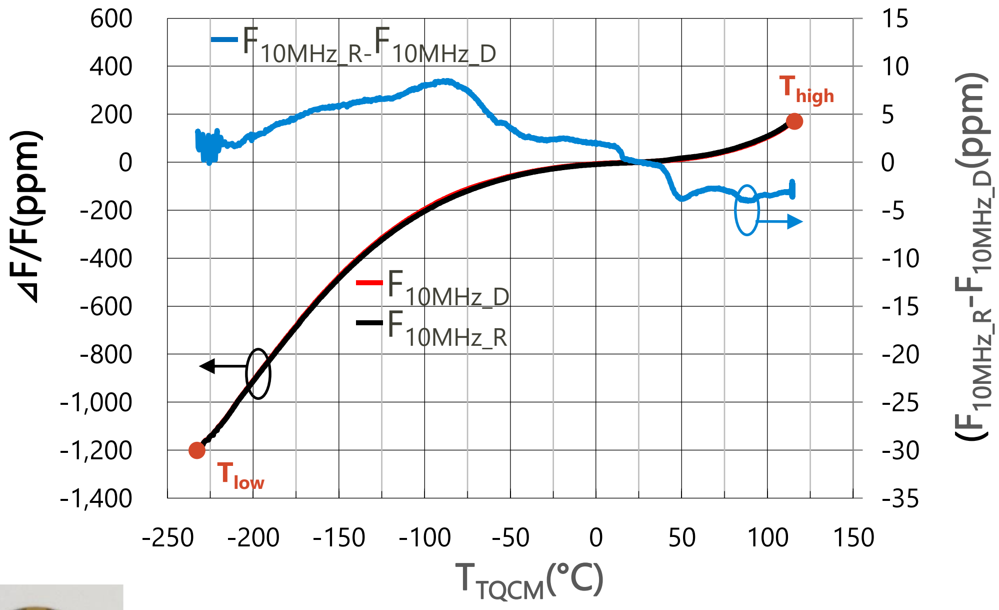
- Highest temperature reaches to 113℃ (Δt=346℃)
- Stably return to T_{low}

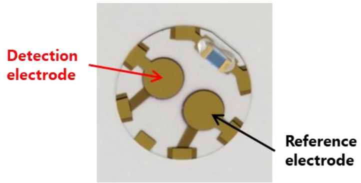


*F_{10MHz_D} : 10MHz normalized Frequency of Detection electrode
F_{10MHz_R} : 10MHz normalized Frequency of Reference electrode

Oscillation vs. temperature characteristics

Cancellation characteristics as differential signal during heating





Result

Between T_{low} and T_{high},

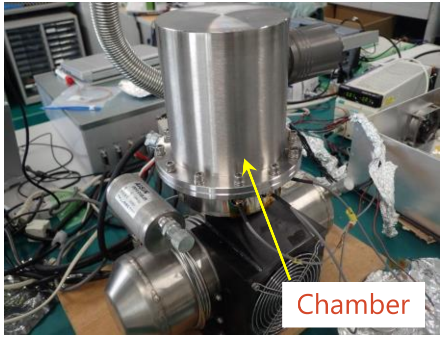
- Both of F_{10MHz_R} and F_{10MHz_D} varied about 1400ppm(14kHz)
- F_{10MHz_R} - F_{10MHz_D} varied within ±10ppm

➡Cancellation based on "Twin"-TQCM works very well

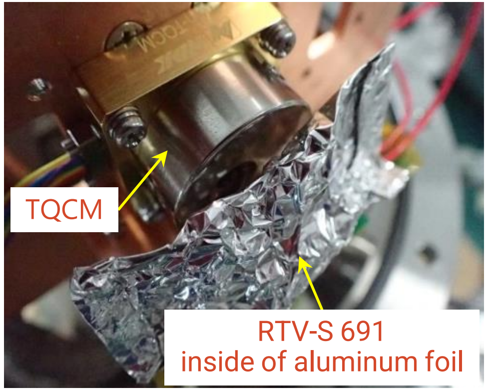
*F_{10MHz_D} : 10MHz normalized Frequency of Detection electrode

F_{10MHz_R} : 10MHz normalized Frequency of Reference electrode

RTV-S 691 deposition characteristics



NDK's cryogenic chamber



Inside of chamber

Conditions

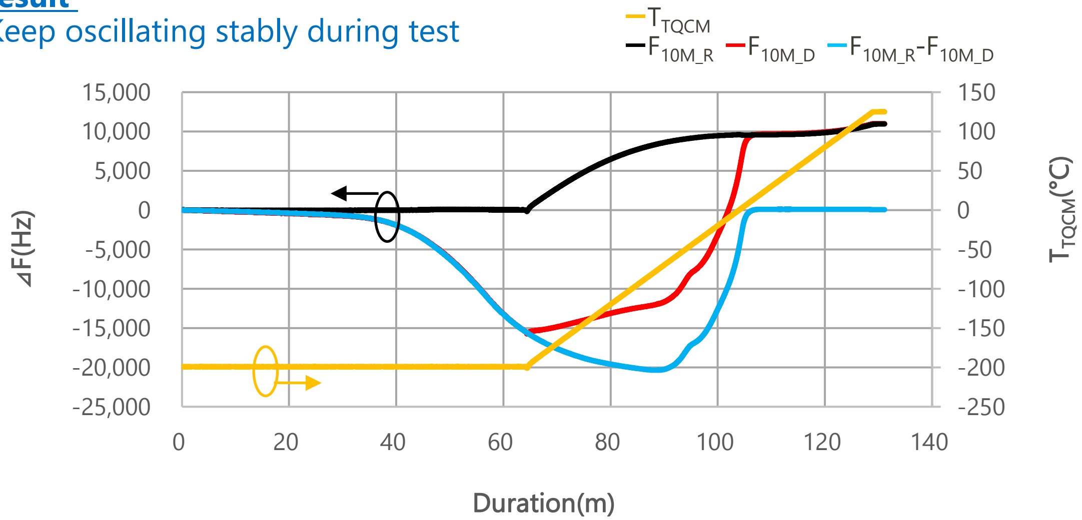
- Use NDK's cryogenic chamber(Lowest temperature is -223℃ at T_b)
- Temperature ramp rate: 5℃/min
- Vacuum pressure: <10^{-3}Pa

Protocol

a. Set T_b to -199℃
b. Heat the sample
c. Keep T_{TQCM} at -199℃ and start measurement until frequency change by 20kHz
d. Start baking with above ramp rate to 125℃

Result

Keep oscillating stably during test



Other evaluations: Vibration and shock

Test result of Vibration and shock with Ground model

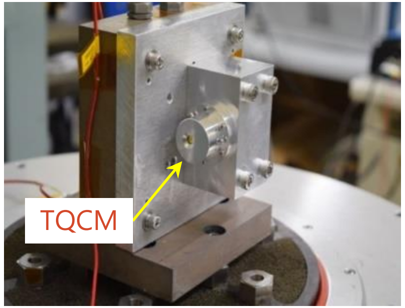
We have tested as below with Ground model
and will test with new Flight EM till Nov. 2023.

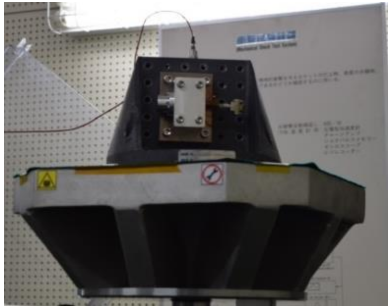
<u>Conditions</u>

・Random vibration:
14.1 grms/at least 120sec, In-plane axis
19.7 grms/at least 120sec, Out-of-plane axis
・Shock: 1000G/1msec, all axes

<u>Result</u>

Pass





Example of test scene

Other evaluations: Radiation

We have tested radiation irradiation test with Flight BBM
and confirmed that no SEE occurred in Sensor module.
Now we are designing countermeasures for SoC FPGA on Controller
and will confirm the effectiveness in Nov. 2023.

Vacuum chamber for radiation test
at Tsukuba University.

Controller board
is inside

Proton irradiation test
at WERC.

Controller board
and Oscillation board

*WERC: Wakasa wan energy and research center

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Conclusion

- NDK and JAXA have been developing PFM of Twin-TQCM toward Mar. 2025
- At 40K, problems have been almost solved.
  Need to test with increased quantities and confirm the margin for each characteristics in detail
- Evaluate miniaturized EM0 controller in detail and install functions
- Complete Vibration, Shock, Radiation and other tests
- Looking for good customer!

Thank you for your attention!

Questions?

More information on NDK's Twin-QCM:
Outgas Analysis System | Products | NDK - NIHON DEMPA KOGYO CO., LTD.