Design and manufacture of high-precision dilatometer for low-thermal-expansion materials for EUVL

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Abstract

The low-thermal-expansion materials (LTEMs) used in EUVL must have a near-zero coefficient of thermal expansion (CTE). Unfortunately, the resolution of commercial dilatometers is too low to accurately measure the properties of LTEMs. So, LTEM suppliers have developed their own CTE metrologies for their research. However, from the standpoint of LTEM users, standardization of the metrology is desirable. For this purpose, ASET formed a team consisting of AIST and seven LTEM suppliers. AIST possesses a very precise CTE metrology system employing a double-path optical heterodyne interferometer and a high-precision thermo-controlled specimen chamber. Our team has developed a practical dilatometer based on the AIST technology and specialized to meet EUVL requirements. First, ASET queried LTEM suppliers to learn their CTE metrology requirements for LTEM development (including information on specimen size, measurement temperature range, etc.), and determined the specifications of the dilatometer. Next, the sources of uncertainty were considered, and the design of the dilatometer was optimized. A prototype dilatometer has been constructed, and the performance is now being assessed. The expanded uncertainty (k=2) of CTE measurements should be 2 ppb/K. Some of the performance data is also due to be reported. This study was supported by NEDO.

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2. Technology development target
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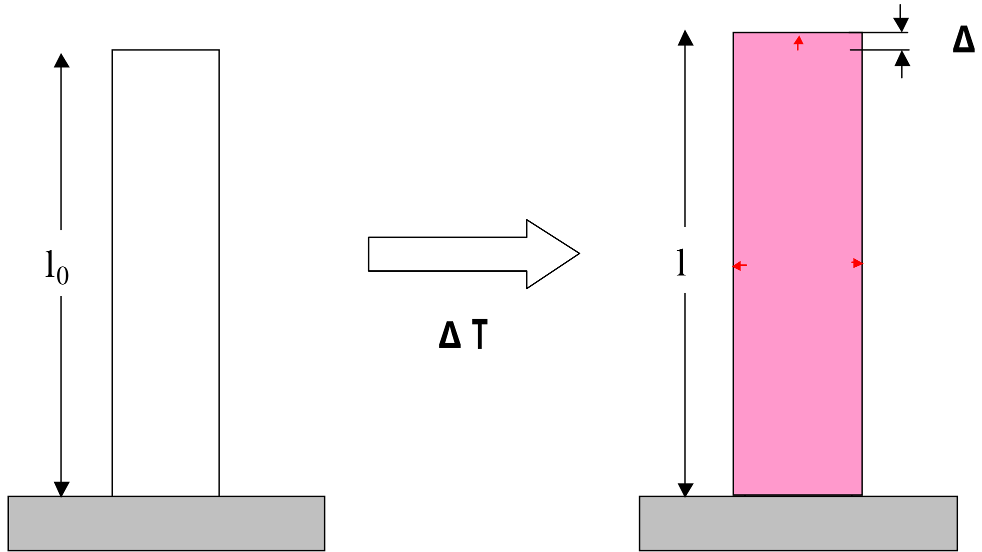
Background ： CTE definition

CTE：Coefficient of Thermal Expansion



$$\alpha = \frac{\Delta l}{l_0} \cdot \frac{1}{\Delta T}$$

CTE of the general LTEMs

Quartz：1ppm，SUS304：20ppm，

Al_2O_3：7ppm，Si_3N_4：4ppm

Background : The necessity for LTEMs in EUVL

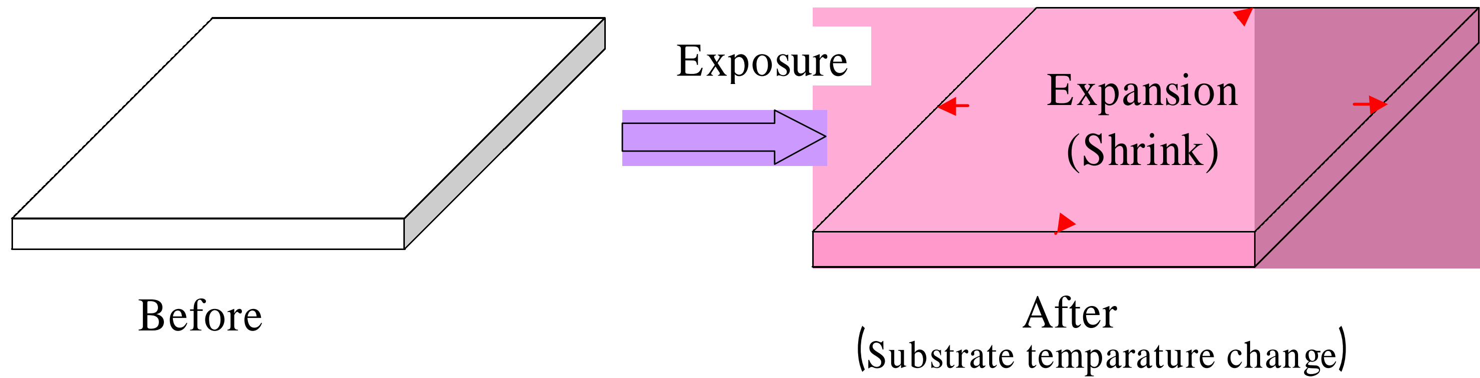


Fig. Schematic figure of the mask deformation under exposure

SEMI standards (Mask substrate)

0±5ppb/℃ (19−25℃)

1ppb = 0.1nm (@10cm specimen)

Background : CTE metrology

Metrology required in early stages of LTEMs development ： absolute measurement

Classification	Measuring method	Advantage	Disadvantage	Usage
Comparison measurement	Ultra-sonic velocity	Easy (sample preparration and measurement)	High precision reference sample is essential	Metrology for mass production
	Stoichiometry			
	Refractive index			
	Push rod	High accuracy		Development, Reference sample measurement
Absolute measurement	Optical interferometry	The highest accuracy, Reference sample is unnecessary	Complicated (sample preparration and measurement)	

Provision standard metrology to LTEMs maker is pressing need.

Background : Optical interferometry

In order to obtain resolution of 0.1nm

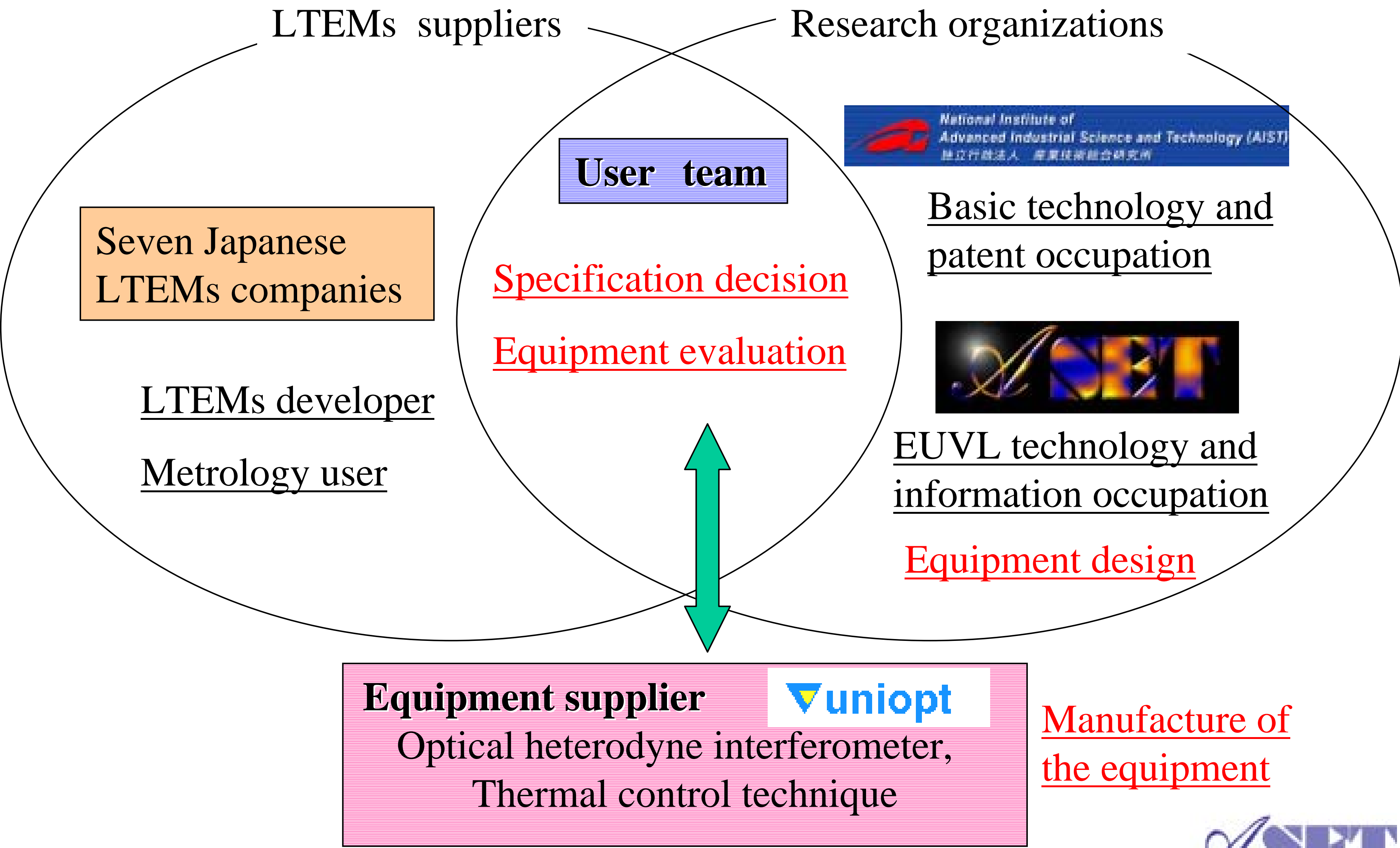
Measuring method	Feature	Accuracy	Marketing equipment
Mickelson interferometer	Intensity measurement	1/100λ, few nm	Existence (ULVAC-RIKO, Inc.)
Optical heterodyne interferometer	Phase measurement	1/1000λ, sub-nm	Non-existence

Optical heterodyne interferometry has the highest accuracy of CTE measurement

Target of the technology development

- Absolute measurement (Optical heterodyne interferometer)
- Resolution : 1ppb/℃ or less
- Repeatability（3σ）：3ppb/℃ or less
- Practical equipment：Marketable
- Standard metrology

Development scheme



Equipment design ： Core technology

Principle of the optical-heterodyne interferometric measurement

$$E_r = a_r \cos(2\pi f_r t + \phi_r)$$
$$E_s = a_s \cos(2\pi f_s t + \phi_s)$$

$$I = \left\langle \left| E_s + E_r \right|^2 \right\rangle$$: Light intensity of $E_r + E_s$

$$= \frac{a_s^2 + a_r^2}{2} + 2a_s a_r \cos\{2\pi f_b t + \Delta\phi\}$$

$$= \frac{a_s^2 + a_r^2}{2} + 2a_s a_r \cos\{2\pi(f_s - f_r)t + (\phi_s - \phi_r)\}$$

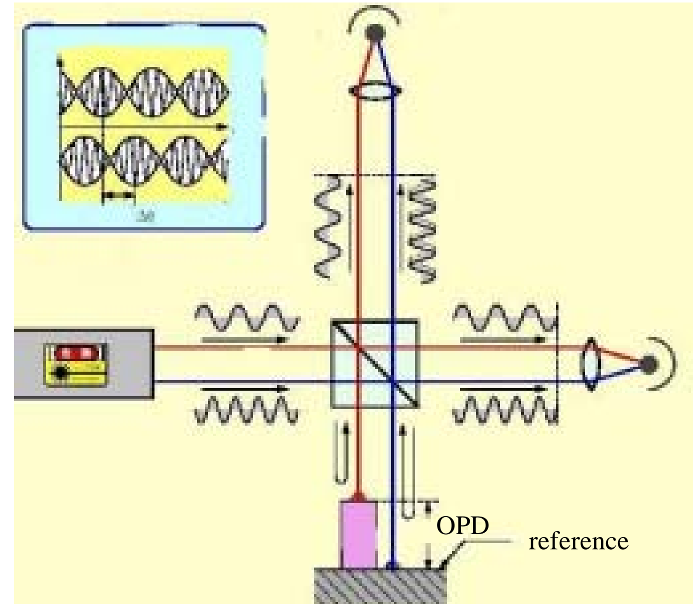


Fig. Schematic figure of the double-path optical-heterodyne interferometer.

Phase difference between PD1 and PD2：

$$\Delta(\phi_s - \phi_r) = \frac{2\pi\Delta L}{\lambda}$$

ΔL：Optical-path-length change

(4 times of specimen length change by thermal expansion)

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Equipment design ： Core technology

Arrangement of a laser interferometer for dilatometry

using an optical heterodyne method with a double-path

Photodetector (for a reference signal)

Polarized cube baem splitter

modulated by 79.9 MHz

modulated by 80.0 MHz

Retroreflector

Cryostat

Photodetector (for a displacement signal)

Specimen

Reflector

Quarter-Wave plates

Acoustooptic modulator

Frequency stabilized laser beam (λ=632.8 nm)

Half-wave plate

Beat frequency : 100 kHz
Resolution of displacement measurement : ~0.1 nm

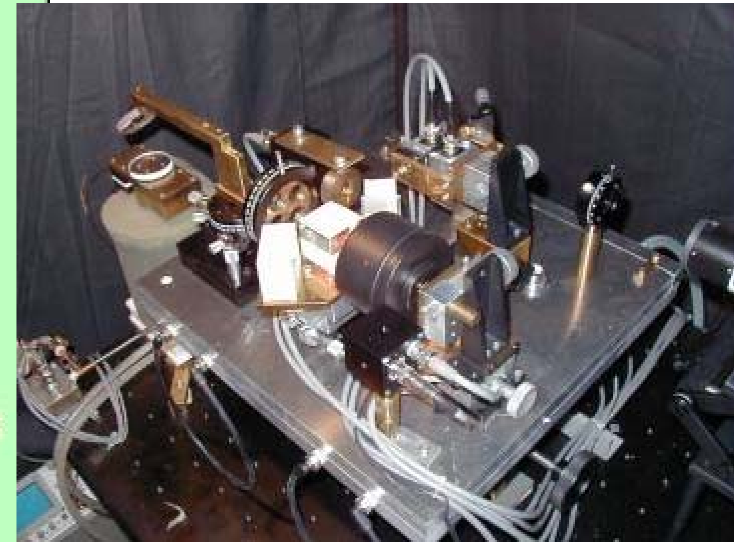

Fig. Schematic figure of the high precision CTE measurement equipment at AIST. This equipment is used for calibration services.

Equipment design : To match the EUVL requirements

To obtain high precision

Approach from uncertainty factor consideration

$$\delta\alpha_{total} = \left(\frac{\delta l_0}{l_0}\right)_{sp} \alpha + \left[\delta\left(\frac{\delta l}{l}\right)\right]_L \frac{1}{\Delta T} + \left[\frac{\delta(\Delta T)}{\Delta T}\right]_T \alpha$$

Determination of the specimen length

Determination of the specimen length change by thermal expansion

Thermo-control stability and determination of the temperature

This term has a little influence

This term has large influence

This term has a little influence

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Equipment design ：Uncertainty factors of the ΔL determination

$$\delta\alpha_{total} = \left(\frac{\delta l_0}{l_0}\right)_{sp}\alpha + \left[\delta\left(\frac{\delta l}{l}\right)\right]_L \frac{1}{\Delta T} + \left[\frac{\delta(\Delta T)}{\Delta T}\right]_T \alpha$$

$$\left[\delta\left(\frac{\delta l}{l}\right)\right]_L = \left[\delta\left(\frac{\delta l}{l}\right)\right]_{las} + \left[\delta\left(\frac{\delta l}{l}\right)\right]_{fri} + \left[\delta\left(\frac{\delta l}{l}\right)\right]_{tilt} + \left[\delta\left(\frac{\delta l}{l}\right)\right]_{mir} + \left[\delta\left(\frac{\delta l}{l}\right)\right]_{air}$$

Canceled by the vacuum chamber

$$\left[\delta\left(\frac{\delta l}{l}\right)\right]_{las} = \frac{4l_0}{\lambda}\cdot\delta\lambda$$

：Laser frequency error
δλ：1.0×10-9nm or less is needed

$$\left[\delta\left(\frac{\delta l}{l}\right)\right]_{fri} = \delta(\Delta(\phi 1-\phi 2))\cdot\frac{\lambda}{2\pi}\cdot\frac{1}{l_0}$$

：Phase measurement error (digital lock-in amplifier performance 0.1deg or less)

$$\left[\delta\left(\frac{\delta l}{l}\right)\right]_{tilt} = l_0\times(1-\cos\theta)\cong l_0\theta^2$$

：Specimen inclination error、20sec or less is needed

$$\left[\delta\left(\frac{\delta l}{l}\right)\right]_{mir} = \delta T_{mir}\cdot\alpha_{mir}$$

：Metal thickness error

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Equipment design : To avoid an inclination of the specimen during measurement

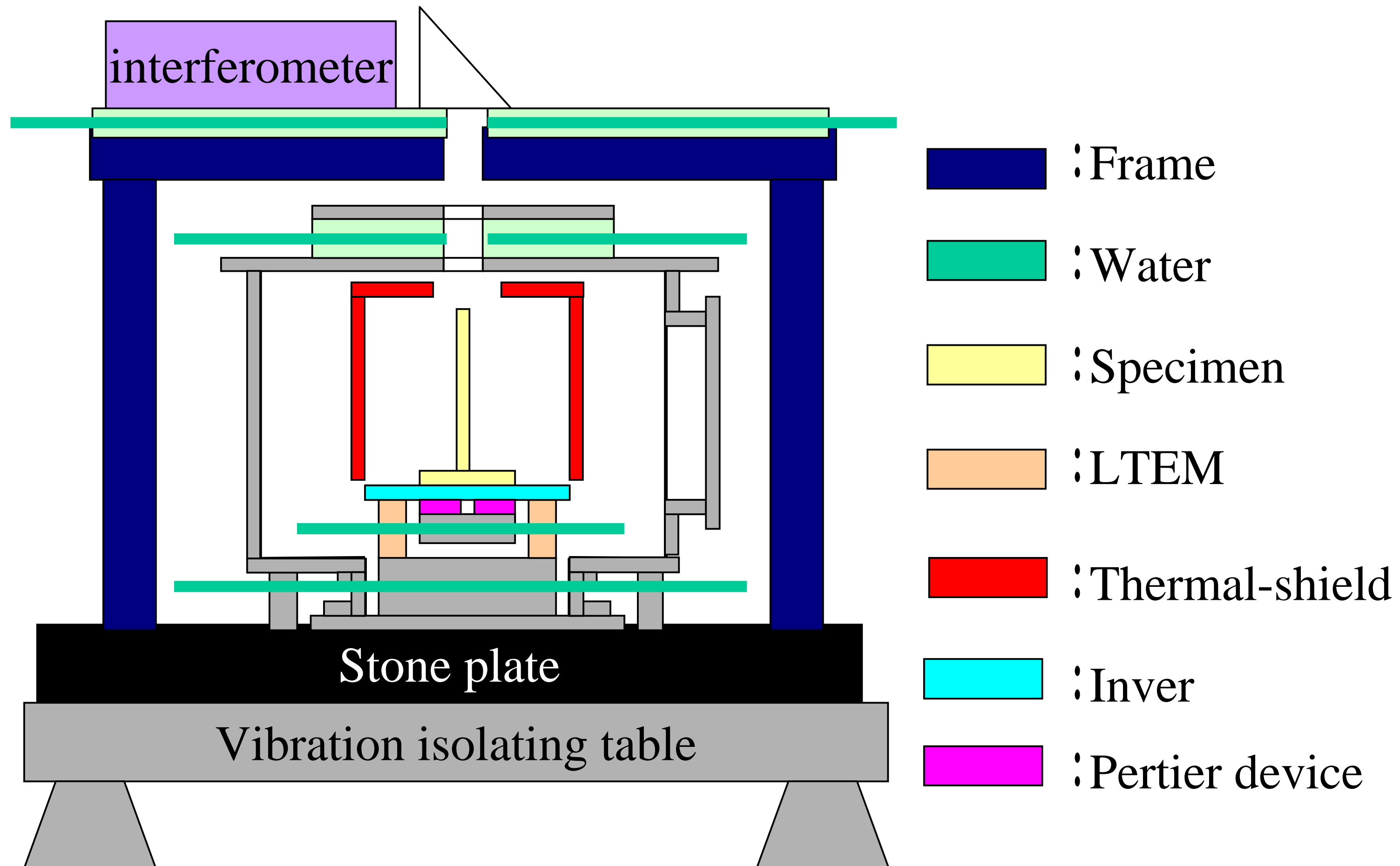
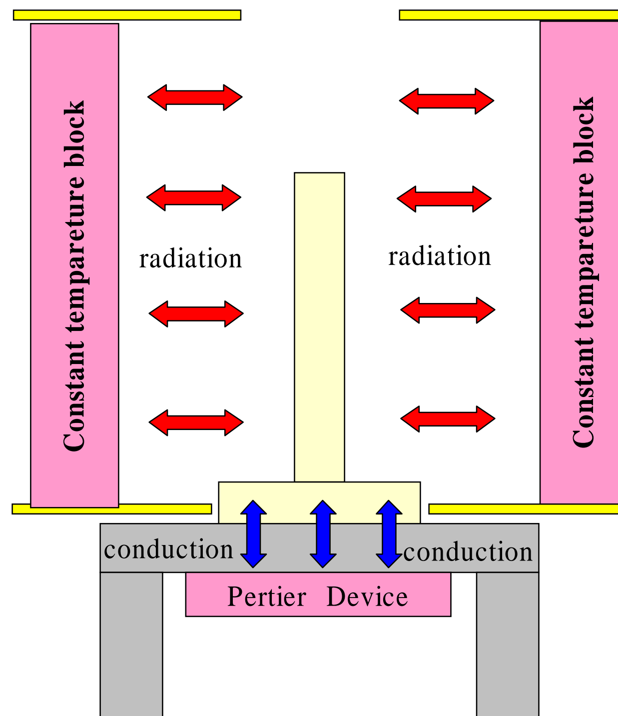


Fig. Schematic figure of the construction of the dilatometer

Equipment design : Uncertainty factors of the thermal-control and ΔT determination

$$\left[\frac{\delta(\Delta T)}{\Delta T}\right]_T = \left[\frac{\delta(\Delta T)}{\Delta T}\right]_{res} + \left[\frac{\delta(\Delta T)}{\Delta T}\right]_{flc} + \left[\frac{\delta(\Delta T)}{\Delta T}\right]_{cal}$$

Resolution of the thermometer | Temperature fluctuation | Determination of the temperature



High efficiency：

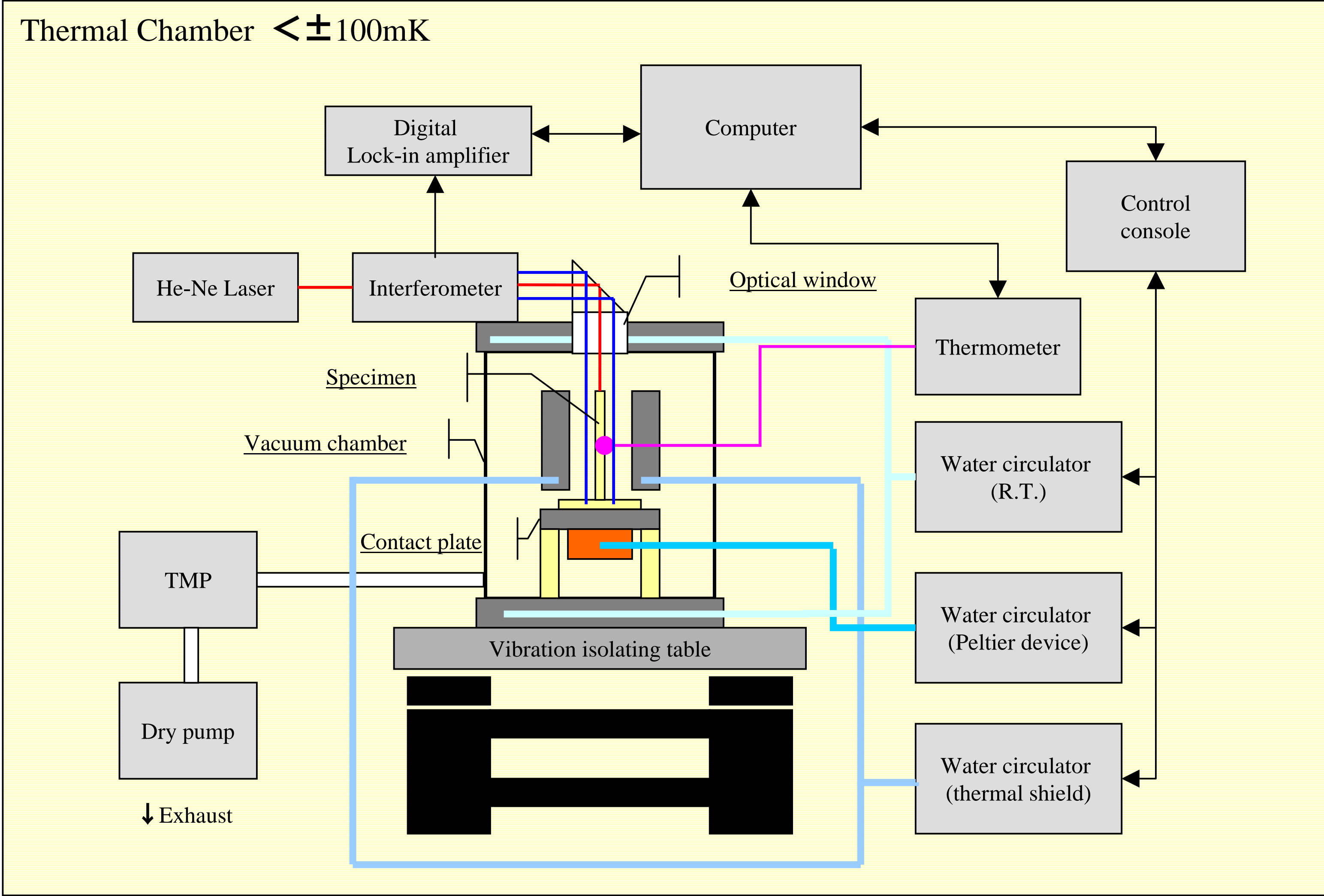
Constant temperature blocks

High precision：

Pertier Device

Fig. Schematic figure of the thermo-control system

System flow diagram

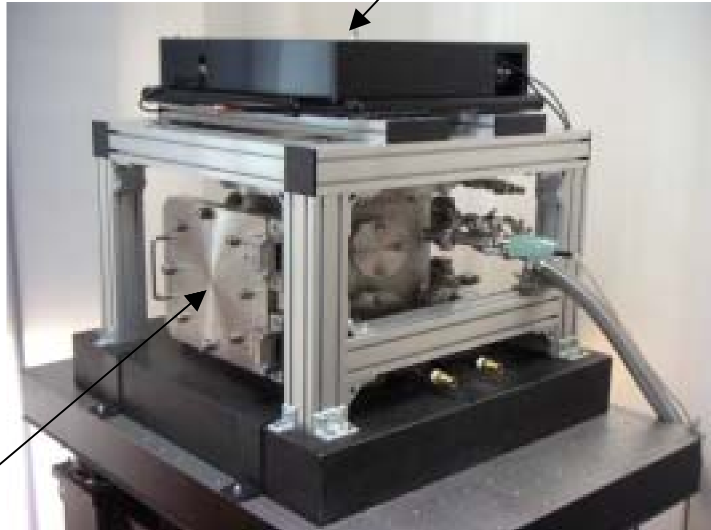


Specifications

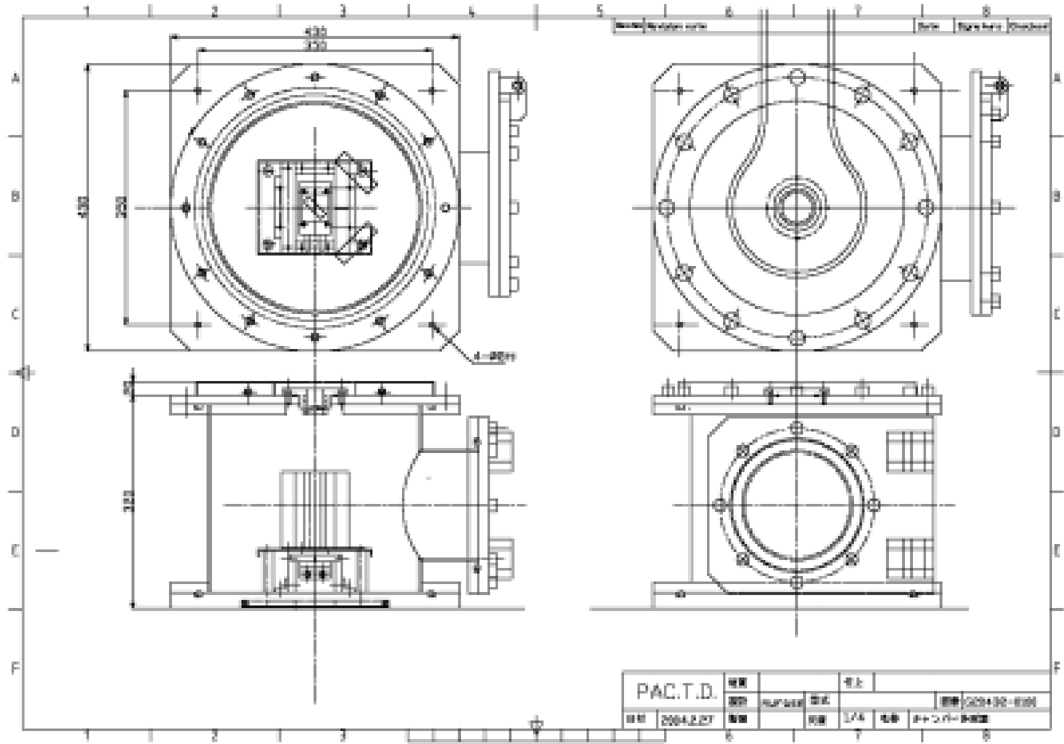
Classification	Items	Specification
Performance	Resolution of phase detection	0.1 [deg]
	Thermal-control accuracy of the specimen	±0.1 [℃]
Specimen	Specimen size	W:35×T:10×L:100 [mm]
System	Light source	Frequency stabilized He-Ne LASER
	Interferometer	Optical heterodyne interferometer
	Frequency modulation	Acoust-optical-modulater
	Beat frequency	25 [kHz]
	Photo detector	APD
	Phase detector	Digital lock-in-amplifier
	Thermal-control	Water circulation + Pertier devices

Manufacture of the equipment : Vacuum chamber

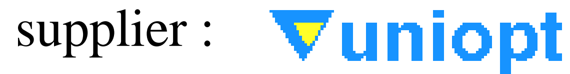
He-Ne Laser,
Interferometer



Specimen exchange door



supplier :



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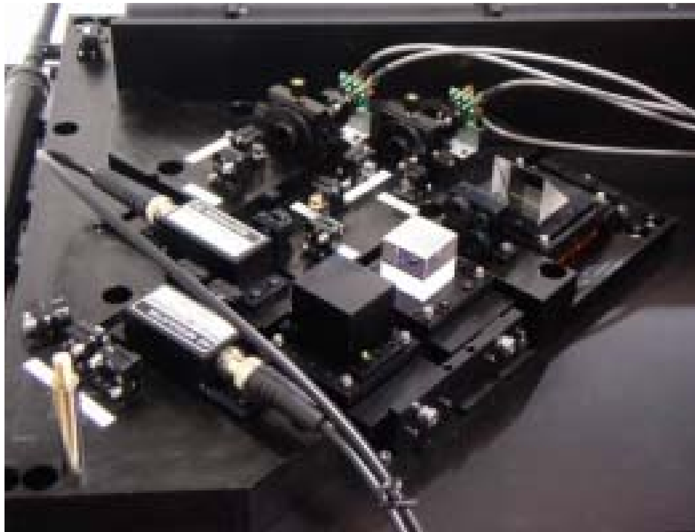
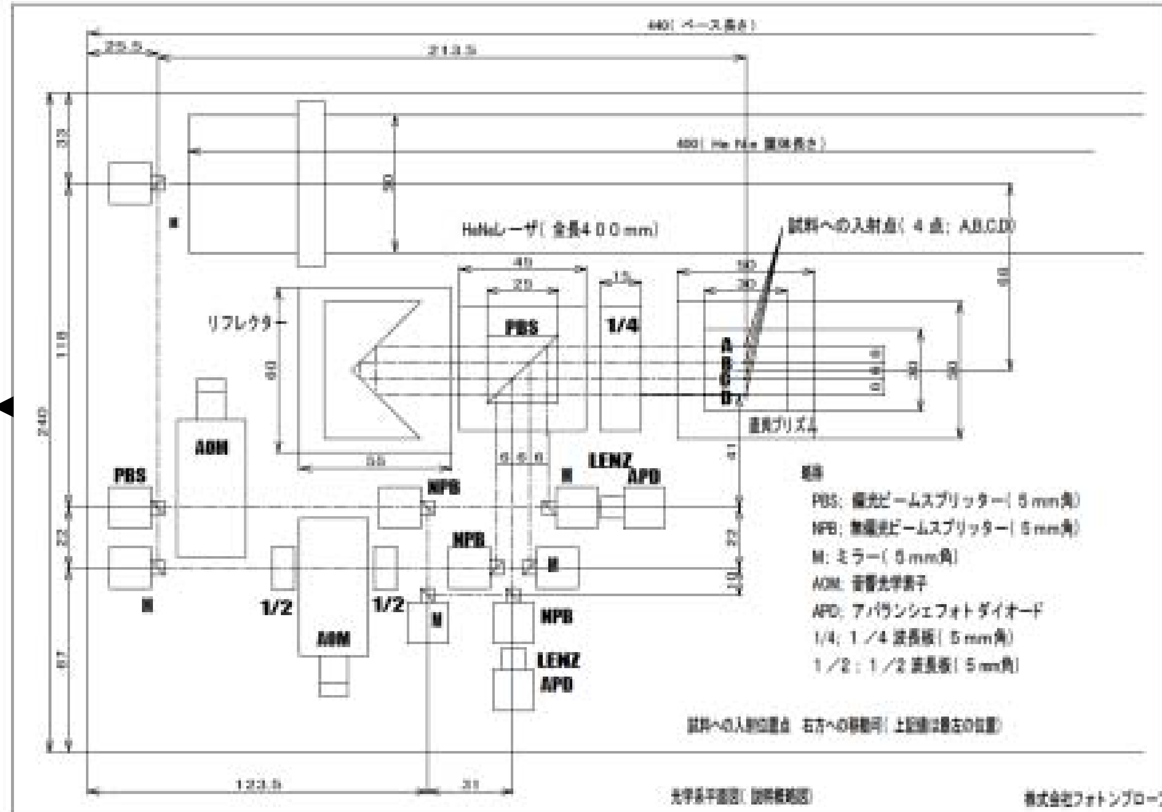
Manufacture of the equipment : He-Ne Laser & Interferometer

Optical heterodyne interferometer : Compact design





Frequency stabilized
He-Ne Laser

MOC-YS-303

Specifications

Frequency stability : $<10^{-11}$

Output power : 3mW

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Manufacture of the equipment : Thermal control unit

Heat source : Thermal shield (radiation) & Peltier devise (conduction)

Thermal shield

open close

LTEM for contact plate and support :

CLEARSERAM® Z-HS OHARA®

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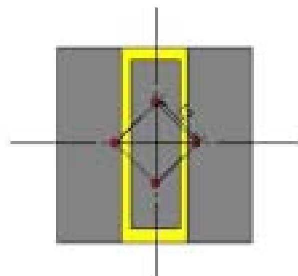
Specimen

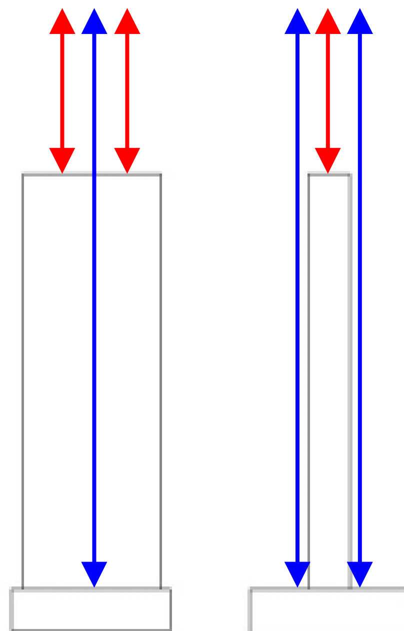
Optical path

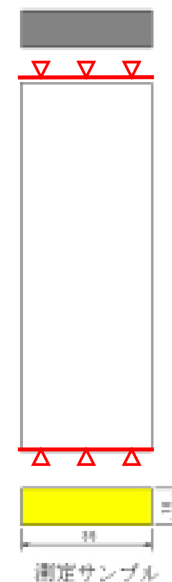
reference

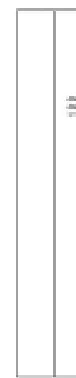
displacement

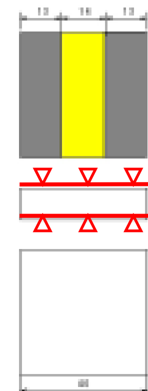


Arrangement of Laser spot



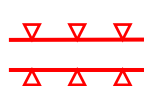






Optical contact

Mirror



parallelism:5sec

flatness:1/10 λ

Summary

- ASET, AIST, and LTEM suppliers have started the development of the practical dilatometer for low-thermal-expansion materials used in EUVL.
- The design of the dilatometer is based on the AIST's CTE metrology system, which employing a double-path optical heterodyne interferometer.
- The sources of uncertainty were considered, and the design of the dilatometer was optimized.
- A prototype dilatometer has been constructed, and the performance is now being assessed.

This study was supported by NEDO.