Design and temper nanometre

ASML's current IC production machines operate with such accuracy that positioning precision requirements are in the order of a nanometre. This makes very high demands on the stiffness and dynamics but certainly also on the thermo-mechanics of the design. Besides thermal expansion, other thermal and thermo-mechanical characteristics must be taken into account. It is also important that the method of thermal conditioning is tuned to the thermo-mechanical behaviour and vice versa. Only then can a good assessment be made and the best concept be chosen.

This article was previously published (in Dutch) in Mikroniek 2006, no. 6.

• *Sjef Box* •

From a technical point of view, an interesting spectacle takes place in the heart of a wafer scanner, around the projection lens. The original (reticle) and the substrate (wafer) are moved with nanometre precision at a speed of around one metre per second; the reticle at the top side of the projection lens, the wafer at the underside, in opposite directions. At the end of the stroke, the direction of movement is reversed and the reticle is scanned again and projected onto the wafer. This process is continued until the entire wafer has been exposed. ASML machines process more than a hundred wafers per hour.

To give an idea of the physics: the dimensions of a projection lens are dependent on the type of machine but are typically one metre in length and several tens of centimetres in diameter. The diameter of the wafers is 30 cm and the number of images per wafer is around a hundred, depending on the customer's IC design.

In order to achieve the necessary speed and acceleration, strong actuators are needed to drive the stages to which the wafer and reticle are attached. Because of this, many kiloWatts are dissipated in a limited space, while, a few centimetres further on, a thermal stability at milli-Kelvin level and lower is required.

The standard solution for a design for ultra-precision positioning is often the use of materials with a very low thermal expansion coefficient. This results in a relaxation of the temperature requirements. This however does not always have to be the best solution possible. A design based upon a low thermal expansion material often has disadvantages in the field of material or production properties or costs, which do not outweigh the relaxation of the thermal specifications in terms of materials, production and cost price. This is illustrated using a real-life example, the design of a metrology frame for the ASML TWINSCAN™ machine.

ature control for precision

ASML Twinscan

ASML has been marketing the Twinscan for several years now. With this machine, the position of the wafer in relation to the wafer stage together with the wafer height map is determined exceedingly accurately in the machine's measurement section; in Figure 1, a schematic overview of the machine is shown. After this, the stage with the wafer moves from the measurement towards the projection section of the machine where the wafer is exposed. The geometric data obtained shortly before is used to position the wafer under the projection lens as accurately as possible, using six degrees of freedom.

A design with two wafer stages creates the possibility to measure and expose a wafer simultaneously. In this way, the most expensive parts of the machine, the optical components, are used virtually continuously and therefore as efficiently as possible. As a result of this, the production speed is very high.

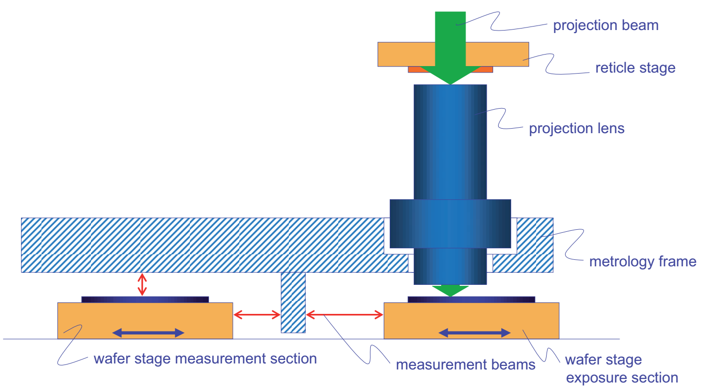

Figure 1. Schematic overview of the ASML Twinscan machine.

The metrology frame

At the heart of the machine the metrology frame is located. This frame connects the projection lens to the sensors that determine the position of the stages in relation to the lens as well as other sensors. Because of this, a distortion of the metro-frame between lens and sensor, or between sensors, immediately results in a measurement error. This is why the specifications for the thermal drift during measurement or exposure of a wafer are in the order of 1 nanometre. Because the machine must also remain stable at a relatively low production speed, a typical short-term stability time period of 5 minutes is maintained. In most cases, the long-term specification is automatically met if the short-term specification is met. This is why only the short-term specification is taken into account in this article.

It is particularly important that the metrology frame remains stable during measurement and exposure of a wafer. It is, therefore, mostly the changes in the heat load on this frame that lead to thermo-mechanical drifts during or at the start of these processes, which, in turn, lead to measurement inaccuracies. A first-order estimation of the fluctuations in the heat load on a Twinscan metrology frame is shown in Figure 2.

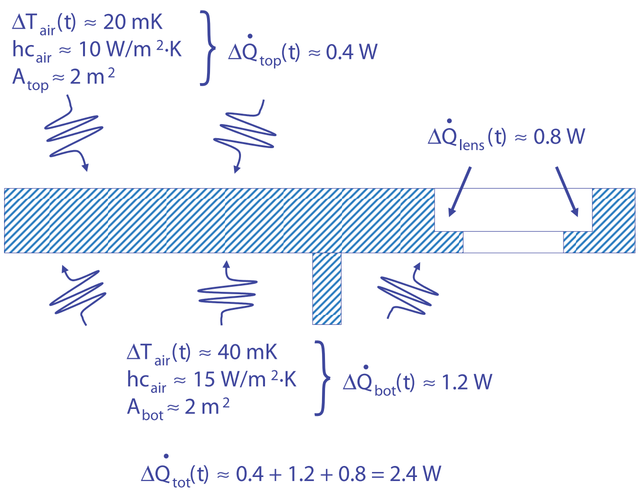

Figure 2. Fluctuating heat load on a Twinscan metrology frame.

On the top side, the surrounding air typically fluctuates with 20 mK. With a heat transfer coefficient of approximately 10 W/m^2·K and an upper surface area of approximately 2 m^2, the result is a heat load fluctuation on the upper side of approximately 0.4 W. As a result of the fast movements and the high power dissipation of the wafer stages at the underside, the air temperature fluctuations as well as the effective heat transfer coefficient are higher. As a result of this, the power fluctuation at the underside will amount to approximately 1.2 W. Transmission losses in the projection lens also lead to power fluctuations, for example when starting production or after changing the reticle (original). The typical fluctuation of the heat load of the projection lens is 0.8 W. Therefore, the total fluctuation of the heat load on the metrology frame is approximately 2.4 W. Note: in addition to the abovementioned heat loads, there are also components that create a fluctuating heat load directly onto the metrology frame. These values are relatively small and are not considered here, for the sake of simplicity.

Alternative materials

Traditionally, the metrology frame is constructed of invar and typically weighs 1,500 kilograms. The weight is important with regard to the dynamic insulation from outside vibrations. The traditional frame consists of a welded sheet metal construction (see Figure 3).

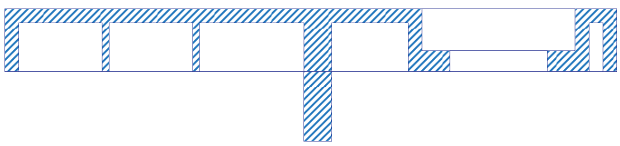

Figure 3. Schematic view of the traditional invar sheet metal frame.

The disadvantages of this type of frame are:

- a very high cost price;
- a long lead time (typically six months).

Mainly because of the very high price, it was decided to look for an alternative design. This study showed that a solid aluminium design is the most interesting alternative; see Figure 4. In Table 1, several important characteristics of both materials are compared with each other. The fact that is most striking is that the thermal expansion coefficient is approximately 13 times higher. Because of this, the design initially caused great amazement. Also from a first-order estimation of the thermal drift, an aluminium metrology frame seems much worse than the traditional design.

Table 1. Material properties of invar and aluminium.

		Invar	Aluminium [1]
Density	ρ [kg/m³]	8,030	2,660
Specific heat	C [J/kg·K]	500	900
Heat conduction coefficient	k [W/m·K]	14	122
Thermal expansion coefficient	CTE [1/K]	$1.8 \cdot 10^{-6}$	$24 \cdot 10^{-6}$

[1] Pure aluminium is not suitable with regard to construction and production techniques. The properties shown here are those of aluminium that is alloyed in order to achieve good machinability; the main effect of this is a strong decrease of the heat conduction coefficient.

Figure 4. Solid aluminium metrology frame.

Thermo-mechanical behaviour

For a first-order estimation of the temperature drift, it is assumed that the system roughly behaves like a first-order system. In that case, the metrology frame in thermal equilibrium will display a typical exponential variation in temperature over time after a stepwise change in the heat load; see Figure 5.

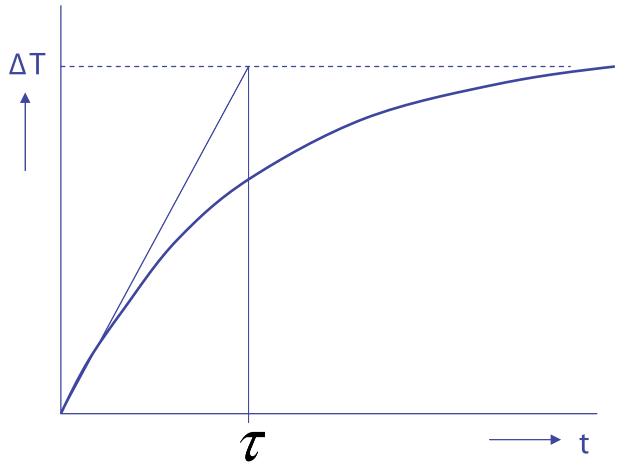

Figure 5. First-order behaviour of a thermal system.

Immediately after the stepwise change, the temperature increase is only a function of this change and the heat capacity of the frame. The following applies for this initial uniform temperature change:

$$\Delta Q_{MF} = m_{MF} \cdot C_{\text{invar}} \cdot \frac{dT(t_0)}{dt}$$

$$2.4 = 1{,}500 \cdot 500 \cdot \frac{dT(t_0)}{dt}$$

$$\frac{dT(t_0)}{dt} = 3.2 \cdot 10^{-6}\ \text{K/s}$$

Because the thermal time constant of the metrology frame is much larger than the short-term stabilisation time of 5 minutes (this will be confirmed later), this initial temperature drift can be used to determine the heating up after 5 minutes:

$$\Delta T_{\text{invar}}\,(t = 5\ \text{min}) = 5 \cdot 60 \cdot 3.2 \cdot 10^{-6} = 1.0 \cdot 10^{-3}\ \text{K}$$

The typical length of the measurement beams is 0.5 m and using the thermal expansion coefficient of invar, the uniform expansion can be estimated (it will be checked later if this calculation is valid for this design):

$$\Delta L_{\text{invar}}(t=5\,\text{min}) = L_{\text{meas.}} \cdot CTE_{\text{invar}} \cdot \Delta T(t=5\,\text{min}) =$$
$$0.5 \cdot 1.8 \cdot 10^{-6} \cdot 1 \cdot 10^{-3} = 0.9 \cdot 10^{-9}\ \text{m}$$

So, the uniform expansion of the invar metrology frame is approximately 1 nm and complies with the specifications. If we perform the same exercise with an aluminium metrology frame of the same compulsory weight of 1,500 kg, the heating-up after 5 minutes equals:

$$\Delta T_{\text{alu}}(t=5\,\text{min}) = 0.53 \cdot 10^{-3}\ \text{K}$$

However, with the expansion coefficient of aluminium, the uniform change in length is equal to:

$$\Delta L_{\text{alu}}(t=5\,\text{min}) = L_{\text{meas.}} \cdot CTE_{\text{alu}} \cdot \Delta T(t=5\,\text{min}) =$$
$$0.5 \cdot 24 \cdot 10^{-6} \cdot 0.53 \cdot 10^{-3} = 6.4 \cdot 10^{-9}\ \text{m}$$

This clearly exceeds the specified value and it could therefore be concluded that aluminium is not a suitable material for the metrology frame. This conclusion however is not correct because the completely different thermo-mechanical behaviour is not taken into account nor the associated possibilities of thermal conditioning.

Apart from uniform thermal expansion, the thermal time constant τ, the thermal penetration depth δ and the relationship between the internal and external thermal resistance of an object as defined in the Biot number are also important. The thermal time constant can be calculated as:

$$\tau = \frac{m \cdot C}{\sum hc \cdot A}$$

In which τ = thermal time constant [s]
m = mass [kg]
C = specific heat of the material [J/kg·K]
hc = heat transfer coefficient [W/m^2·K]
A = surface area [m^2]

For the thermal penetration depth (defined as the maximum depth of penetration from the surface inwards of a fictitious linear temperature curve with the same thermal energy as the real temperature curve) at a constant heat flux, the following applies:

$$\delta(t) = \sqrt{\pi \cdot \frac{k}{\rho \cdot C} \cdot t}$$

In which $\delta(t)$ = thermal penetration depth [m]
k = heat conduction coefficient [W/m·K]
ρ = material density [kg/m^3]

The Biot number is defined as

$$Bi = \frac{hc_{external} \cdot L}{k}$$

In which Bi = Biot number [-]
hc_{external} = the external heat transfer coefficient [W/m^2·K]
L = characteristic dimension [m]
k = heat conduction coefficient of the material [W/m·K]

It is often used as a rule of thumb that the temperature distribution of an object can be regarded as uniform if the Biot number is less than 0.1, i.e. the thermal resistance towards the environment exceeds the internal resistance by at least one order of magnitude.
A comparison of all the abovementioned properties provides a better picture of the thermo-mechanical behaviour of both materials; see Table 2.

Table 2. Comparison of thermo-mechanical properties of invar and aluminium.

	Invar	**Aluminium**	**Ratio aluminium/invar**
Uniform expansion after 5 min.	0.9 nm	6.4 nm	7.4
Thermal time constant	4.2 hrs	7.5 hrs	1.8
Thermal penetration depth after 5 min.	0.057 m	0.22 m	3.9
Biot number	0.46	0.05	0.11

This comparison reveals that the thermo-mechanical properties of both materials differ considerably. The Biot number of the invar frame shows that a significant non-uniformity in temperature across the measurement length can be expected. The sheet metal construction increases the internal thermal resistance even more, causing the non-uniformity of the temperature to be even greater. In addition, the non-uniformity will increase even more in this non-stationary situation because of the limited thermal penetration depth. The stiffness distribution of such a sheet metal frame is also highly non-uniform. As a result the measurement errors will not so much be caused by a homogenous drift of the frame, but much more by local rotation angles of the design; see Figure 6. For these local effects the ratio between the heat capacity and the heat transfer can be completely different compared to the value as used for the estimation of the thermal time constant of the total frame, furthermore resulting in a completely different transient behaviour.

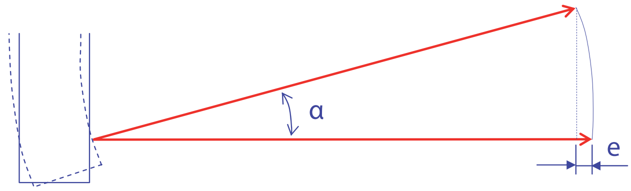

Figure 6. Measurement error as result of localised rotation of the measuring beam.

As a result of the lower density of aluminium, a completely solid frame is possible without exceeding the previously mentioned mass requirements (see Figure 4), causing the internal thermal resistance to be much lower, regardless of material properties. As a result of the combination of the thermo-mechanical properties as shown in Table 2, the measurement errors in the aluminium design will not be caused by local effects but by homogenous deformations.

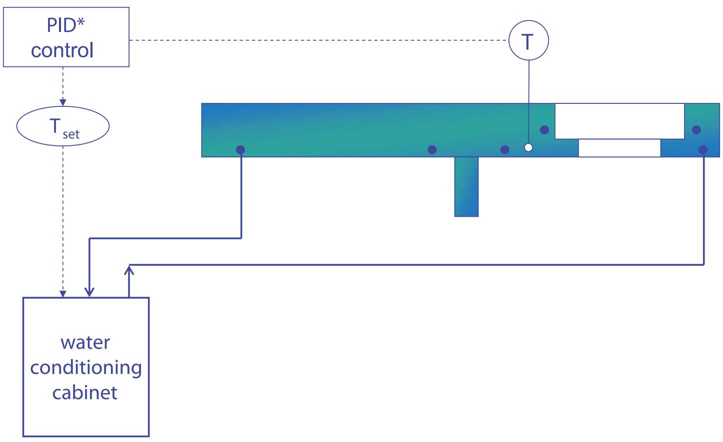

Figure 7. Control algorithm in which the temperature of the metrology frame is included.

Thermal conditioning

If we assume a maximum drift for the metrology frame of 1 nm per 5 minutes, a temperature stability of 0.08 mK per 5 minutes will be required. With the previously described fluctuating heat load on the frame, an active temperature control will be necessary. In a Twinscan, however, water systems are already active for thermal conditioning of the temperature critical components. The aluminium metrology frame can be included in this water system. In that case an adjustment of the temperature control algorithm is required, because the temperature of the metrology frame needs to be included in the setpoint derivation; see Figure 7.

Specifically because of the thermal properties of aluminium, active water conditioning is highly effective. The internal conduction and the thermal penetration speed are high enough to enable excellent conditioning of the entire frame. In addition, the relatively large heat capacity of aluminium ensures that temperature fluctuations, of the environment as well as the cooling water, are dampened very well. This provides an excellent basis for a correct functioning of the temperature control of the frame and its immediate environment. Another advantage of this concept is that the metrology frame now also acts as a thermal stabiliser for the airstreams around the frame, the sensors and the projection lens. In addition, the part of the project lens that is located inside the metrology frame will be conditioned better.

Introduction of aluminium

The aluminium metrology frame can be introduced for all Twinscan machine types, making a great reduction in cost price possible. The lead time will also be reduced from several months to several weeks. This method of applying materials for the design of accurate frames for IC production machines has been patented by ASML.

Author's note

Sjef Box was senior designer at ASML in Veldhoven, the Netherlands, and is now with Philips Applied Technologies in Eindhoven.

Information

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