APPLICATION OF ISO GUIDELINES FOR EVALUATION OF UNCERTAINTY IN PHOTOLITHOGRAPHIC MASK-WAFER ALIGNMENT USING MODIFIED MOIRÉ TECHNIQUE

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ABSTRACT

In the present era of communication and information technology, the complexity of ICs has increased tremendously and line widths have shrunk to submicron level. This requires developments in lithography technologies. Mask to wafer alignment is one of the enabling processes of lithography. In this paper we analyse the sources of error associated with the alignment using modified moiré technique.

1. INTRODUCTION

Last two decades have seen exponential growth of developments in microelectronics industry. The complexity of ICs has increased tremendously and line widths have shrunk to submicron level. The dramatic miniaturization has been possible owing to the new lithographic processes and highly accurate methods for mask to wafer alignment. As development of complex ICs involves multilevel masking, it is necessary to have very accurate automatic alignment independent of operator's skill for high precision and economic viability.

The alignment methods based on moiré technique are capable of giving high alignment accuracy. In this technique moire signal i.e. periodic variation, of light transmitted/reflected form a pair of gratings, is used for alignment. King and Berry[1] were the first to use moiré signal for mask alignment. Since then several alignment methods [2-6] based on moiré technique have been reported. The easiest approach is to use peak or trough of moiré signal for alignment as it offers a unique alignment point. However, the sensitivity of the signal to displacement is least at this point. Our group has proposed a modification of moiré technique by defining an unique alignment point in the higher slope region of the moiré signal in order to achieve higher sensitivity and alignment accuracy[7-11]. This modified moiré technique developed by us has been used for linear (X-Y) alignment with an accuracy of ±50nm using a single pair of gratings an the accuracy of ±4nm was achieved with 2 pairs of gratings. Recently we tried to analyze the sources of errors and their influence on this alignment system[12], as per ISO guide lines. We further extend the scope of error analysis by including a detailed discussion on errors due to A/D conversion errors and correlated errors of various alignment marks. In addition to this, errors due to patterning of alignment marks, changes during the fabrication process, optics used to generate the signal, digitization, environmental effects etc. have been taken into consideration, to evaluate the uncertainty as per the international guidelines[13-15].

2. MODIFIED MOIRÉ TECHNIQUE FOR ALIGNMENT

In moiré technique, a light beam is passed through a grating mark on mask and reflected/transmitted from the corresponding grating mark on the wafer and finally received on a photo detector. The photodetector output varies periodically with the relative displacement of mask and wafer. This periodically varying signal is called moiré signal.
With the arrangement of gratings shown in Fig. 1 the intensity of moiré signal is given by,

$$I = \sum_{m=-M}^{M} \int_{-\frac{w_1}{2}+np}^{\frac{w_1}{2}+np} \int_{-\frac{w_2}{2}+dx}^{\frac{w_2}{2}+dx} \frac{(1+Z/r)^2}{r} e^{-ikr} dx_1 dx_0 \qquad (1)$$

$$\text{where} \qquad r = \sqrt{(z)^2 + (x_1 + mp - x_2)^2}$$

p is the pitch of gratings which is taken as 25µm for computation. λ is Wavelength of the laser source used to illuminate the gratings =0.633µm., parameter m varies from $-M$ *to* M , where (2M + 1)is the number of slits of the gratings,$k=2\pi/\lambda$, is the wave number and Z is gap between the two gratings, $Z=(2n+1)p^2/\lambda$ with n as a variable, W_1 and W_2 are slit width of mask and wafer grating respectively, $W_1=W_2=W=p/2$

The modified moire technique is based on defining a unique alignment point in the higher slope region, by using difference between moiré signal and its phase shifted or inverted version. Two approaches have been used for position control in the higher slope region of moiré signal [8-11].

a) Inverted Signal Method[8-9] and
b) Phase Shifted Signal Method[7,11]

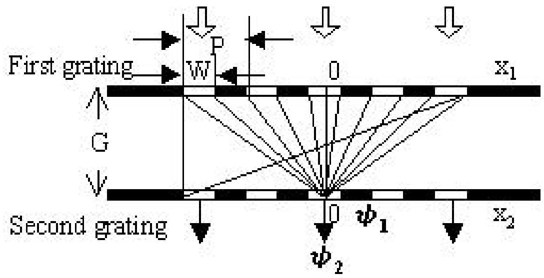


Fig.1 Arrangement of gratings

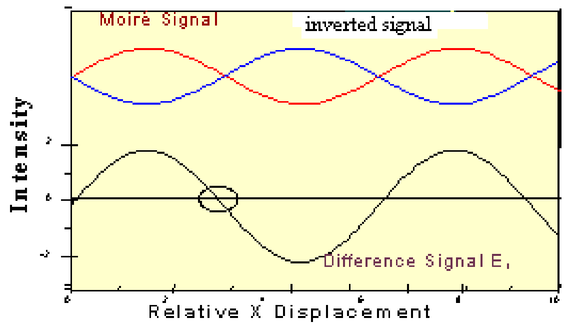


Fig 2 Moire signal, inverted, and difference signal

2.1 Inverted Signal Method

In this method an inverted signal (I_{inv}) is computed from the moiré signal (I), using a single pair of gratings. This inverted signal is given by,

$$I_{inv} = (I_{\max} + I_{\min}) - I \qquad (2)$$

Where I_{max} is maximal and I_{min} is minimal value of moiré signal.

The difference of moiré signal I, and inverted signal generated an error signal IS_1(Fig.2) similar to that of two phase shifted pairs [7]. This signal is used for automatic alignment in the higher slope region.

$$IS_1 = I_{inv} - I = (I_{\max} + I_{\min}) - 2I \qquad (3)$$

2.2 Phase Shifted Signal Method

The phase shifted signals are obtained using two 180° out of phase grating pairs[7]. The difference of these two moiré signals is used for alignment. This has been further simplified by using a single pair of gratings and generating the phase shifted signal (I_p) from the moiré signal, by taking the difference of signal at the points that are half pitch (*p/2*) apart on the displacement axis.

$$I_p = I_x - I_{x+p/2} \qquad (4)$$

Where $\boldsymbol{I_x}$ is value of moiré signal at *x* displacement and $\boldsymbol{I_{x+p/2}}$ is value of moiré signal at *x+p/2* displacement. The difference of moiré signal and the phase-shifted signal is used for alignment.

3. FACTORS INFUENCING ALIGNMENT AND ERROR ANALYSIS

3.1 Definition of Alignment Point

The factors influencing the moiré signal which is used for the definition of alignment position are

Gap (Z), Pitch (P), Wavelength (λ) (Eqn. 1)

The effect of these variations on moiré signal was studied by computer simulation. A point at which the difference signal is zero defines the alignment point. The variations in the influencing factors' can cause shift in alignment position. The effect of these parameters on moiré signal and the alignment point, were studied[12]. These errors are discussed below briefly,

3.1.1 Gap (Z)

Moiré signals were simulated at various values of gap. These are shown in Fig. 3 below. As can be seen from this fig., the change in gap causes change in moiré signal. However, as lithography is carried out in a controlled environment, wafer is held by light vacuum and the system is mounted on a vibration Isolation table to damp the vibration amplitudes to order of tenth of a µm. Therefore the error due to a gap change of 0.3 µm was evaluated and was found to be negligible < 1nm [12].

3.1.2 Intensity (I)

The online calculation of inverted signal is done after storing the values of maximum and minimum of moiré signal in case of a single pair of gratings. Fig. 4 shows the change in alignment position if the laser intensity drifted. It may be seen that alignment point is slightly affected by change in intensity[12].

The effect was of same order for both phase- shifted and inverted signal methods. The total process of alignment and exposure takes about 30-40 seconds and the intensity drift during this period (0.5%) is to be taken into account in the uncertainty budget. In the case of alignment method based on two phase shift pairs of gratings both the signals are generated optically. Therefore the alignment is not affected by the intensity fluctuations.

3.1.3 Wavelength (λ)

A He-Ne laser was used for the alignment experiment and the free running He-Ne laser has a wavelength stability of $1X10^{-6}$, the effect of change in wavelength on alignment point is negligible.

3.1.4 Pitch of the Grating (P)

One percent change in pitch of the gratings may cause a shift of alignment of the order of 10nm. The pitch of the grating does not change significantly during alignment. Even the effect of environmental changes of temperature etc. is negligible(< 0.01%)[12].

3.2 Error Contributions from Experimental Setup

For experiments 25 µm pitch gratings, PZT operated translation and rotation stages, a He-Ne Laser of 20mW and a photodetector were used to generate moiré signal. The moiré signal was fed to computer via A/D cards and the control signal was obtained by computer after performing a PID control loop on the difference (error) signal. This signal was fed to PZT via D/A card to control the alignment. The errors caused by components of experimental setup and their calibration is described below,

3.2.1 A/D and D/A Conversion

The A/D and D/A conversion cards used were 12 bits. These were used in the bi-polar mode having maximum input voltage in the range –5V to +5V. Prior to use, these interfacing cards were calibrated by the high precision calibrator traceable to the 'National Standards' of voltage [16,17]. The uncertainty evaluated is ± 50 µV at ± 5V i.e. 10ppm. The effect of this uncertainty is considered in the next section.

The sampling rate will also have contribution to uncertainty depending on the resolution.

3.2.2 Calibration of Error Signal in Terms of Linear Displacement

The targeted alignment position corresponds to error signal value equal to zero. As the control loop is triggered, the error signal starts reducing and stabilized to zero (Fig. 5). As can be seen here, the difference signal fluctuates around zero. The amplitude of oscillations of the error signal around the zero value is a measure of alignment accuracy. To calibrate these oscillations in terms of shift (nm) in alignment position, a known step of 2.4 µm was induced and the corresponding change in the error signal voltage(610mV) was observed. Thus the sensitivity was estimated to be 254mV/µm.

The relative uncertainty in voltage signal due to conversion card calibration is 10×10^{-6}. The voltage signal display was truncated to 1mV, leading to resolution limits of ± 0.5 mV.
Assuming rectangular distribution, standard uncertainty,

Relative Standard uncertainty value $$u(V) = \frac{0.5}{\sqrt{3}} = 0.288mv \quad (5)$$

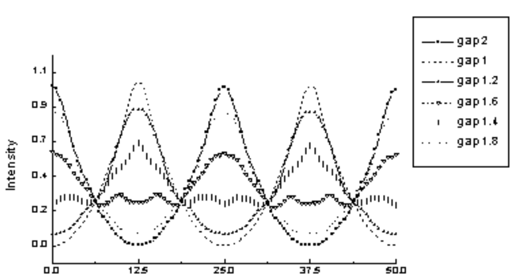


Fig3: Simulated moiré signals at various gap values
(The gap values indicated in insert are multiples of $2p^2/\lambda$.)

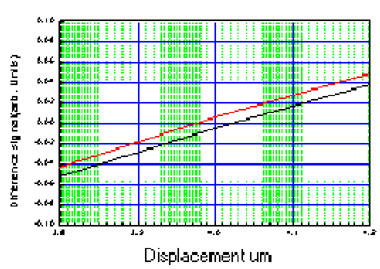


Fig. 4 difference signal Vs Displacement at two intesity levels

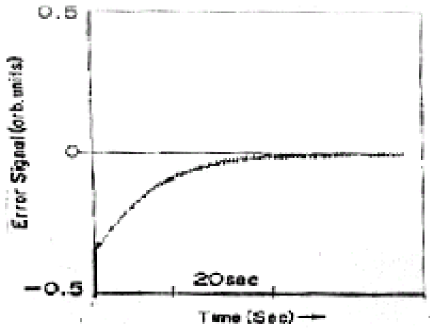
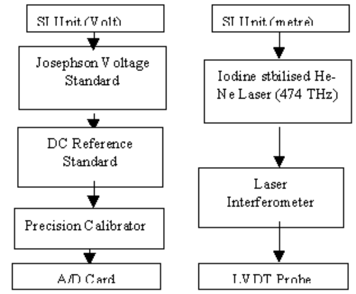


Fig 5 Error (difference) signal at Alignment



Fif 6 Traceability chart for A/D card and LVDT probe

$$\frac{u(V)}{V} = \frac{0.288}{610} = 4.7x10^{-4} \qquad (6)$$

The LVDT probe used for displacement measurement is calibrated with traceability to SI unit 'metre' as shown in fig. 6. This has uncertainty of 30nm at k=2. Thus the standard uncertainty u(L) = 15nm and the relative standard uncertainty

$$\frac{\mathrm{u(L)}}{\mathrm{L}} = \frac{15\mathrm{nm}}{2.4\mathrm{nm}} = 6.25x10^{-3} \qquad (7)$$

Model function the calibration factor

$$C = \frac{V}{L} \qquad (8)$$

As per ISO Guidelines on Uncertainty in Measurement , the combined relative uncertainty is given by

$$\frac{\mathrm{u(C)}}{\mathrm{C}} = \sqrt{\left(\frac{\mathrm{u(L)}}{\mathrm{L}}\right)^2 + \left(\frac{\mathrm{u(V)}}{\mathrm{V}}\right)^2} \qquad (9)$$

The alignment error $A_{E,}$ was obtained by measuring the limits within which the error signal oscillates (V_{osc}) in controlled condition of alignment.

$$A_E = \frac{V_{osc}}{C} \qquad (10)$$

A_E is estimated to be 59.8 nm and its relative uncertainty is given by,

$$\left(\frac{u(A_E)}{A_E}\right)^2 = \left(\frac{u(V_{osc})}{V_{osc}}\right)^2 + \left(\frac{1.u(C)}{C}\right)^2 \qquad (11)$$

Thus $u(A_E) = 6.26 \text{ x } 10^{-3}\text{x } 60\text{nm} = 0.37$ nm

4. EVALUATION OF UNCERTAINTY IN THE REPORTED VALUE OF ALIGNMENT

Uncertainty contribution due to the factors mentioned above are evaluated by type B evaluation method [12-15]. The uncertainty budget given in Table 1is self-explanatory. Contribution of sampling has been taken for a case where 20000 samples are collected for 25 μm. This will lead to sampling resolution of 1.3 nm.

Table 1 Uncertainty budget

Source X_i	**Limit ±**	**Standard uncertainty $u(x_i)$**	**Probability Distribution**	**Sensitivity coefficient c_i**	**Degree of Freedom (ν_i)**	**Uncertainty contribution $u_i(y_i)$**
Gap	0.3 μm	0.173 μm	B, rectangular	calculated 1nm/ 0.3 μm	∞	1nm
Intensity	0.5%	0.29%	B, rectangular	4nm/0.1%	∞	12 nm
Sampling	1.3nm	0.75nm	B, rectangular	1	∞	0.75nm
Experimentally estimated alignment error	60nm	0.4nm	B, rectangular	1	∞	0.37
Combined uncertainty					∞ **(ν_{eff})**	12.1nm
Expanded uncertainty at a confidence level approx 95%, rectangular distribution*, K=1.65						**20nm**

* The overall distribution is taken as rectangular as in this case there is one dominant contribution of 12nm hence central limit theorem will not apply[14].

The alignment obtained an uncertainty ±20 nm at approx 95% confidence level. This uncertainty has been evaluated for mask to wafer alignment in X axis. The same technique is applied to obtain alignment in X, Y, θ axes. In such a case correlations of uncertainty for individual axis need to be considered. By nature of perpendicularity of grating alignment marks for X and Y axis these uncertainties are totally uncorrelated for these two axis. However, the rotational uncertainty is correlated to these. The effect of rotational error and correlation of two alignment marks for X and θ will enlarge the uncertainty further to the order of 35 nm for whole wafer. The alignment accuracy achieved experimentally, reported earlier [8-11] seems to be limited mainly by intensity drift of laser and the sampling resolution of (approximately 13 nm). This component does not play any role in case of two phase shifted pairs of grating method and hence the achievable alignment accuracy is also better [7]. In this case the estimated uncertainty is of the order of 2 nm. To make use of simplicity of single pair grating method it is advised to use intensity stabilized laser in this case to minimize the uncertainty.

5. CONCLUSION

Error analysis has been carried out for the case of mask to wafer alignment using modified moiré techniques. In case of the single pair of grating method the uncertainty is estimated to be about 20 nm, limited mainly by the fluctuations of intensity of laser. In case of two phase shifted pairs of grating method the uncertainty is lower and is of the order of 2 nm.

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