Flatness Definition Studies

SEMI P-37 and SEMI P-40

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SEMI Standard Flatness Definition
Best Fit Plane

SEMI P37-1102

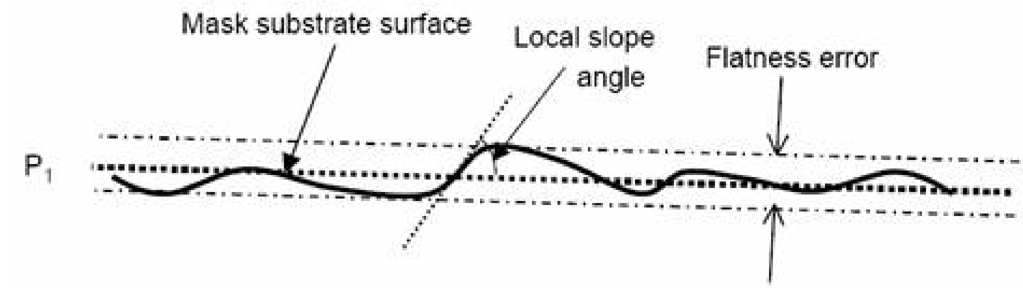

Figure 4
Definition of Flatness Error and Local Slope Angle
P1 is the plane that minimizes maximum deviation of the surface.

SEMI P40-1103

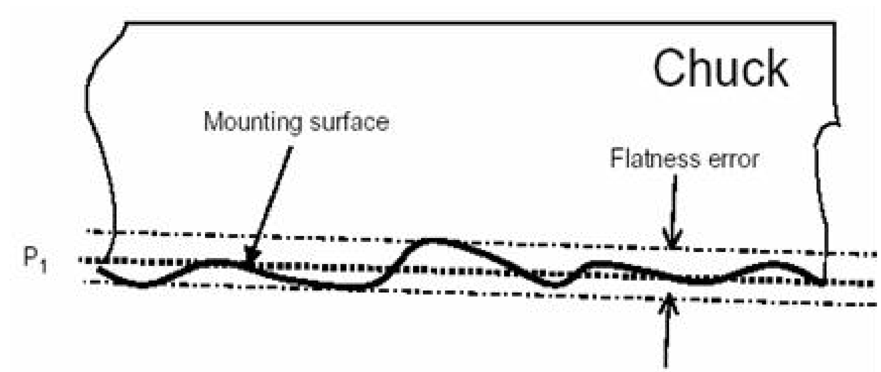

Figure 3
Definition of Flatness Error
P_1 is the best fit plane that minimizes the maximum deviation of the surface from P_1.

Analysis Procedure

- Interferometric flatness data for the front and back surfaces of 12 substrates (before coating) were supplied by SEMATECH.

- The peak-to-valley (*p-v)* nonflatness of each substrate was first found using the Zygo software (Metropro).

- Least squares (LS) and minimax (MM) best fit planes were then fitted to each of these substrate data sets in order to evaluate the differences in the *p-v* nonflatness values between them and compare these with the Zygo software values.

- The perpendicular distance of the raw data points from the best fit plane gives the shape of the substrate surface. This is equivalent to removing the tip and tilt from the data.

- The maximum distance minus the minimum distance gives the *p-v* npnflatness for each case.

- The percentage differences for the three methods were computed using the smaller value as the denominator.

Description of Methods

- ***Zygo Software (Metropro)***
  - Uses Seidel polynomials of the first order to remove tip and tilt and obtain the *p-v* nonflatness.
  - Do not know the exact procedure that is followed but customer support said that the software may be creating additional data points to create a circular shape.

- ***Least Squares Method (Orthogonal Distance Regression)***
  - Input: x, y, z data vectors each of length n, with means $x0, y0$ and $z0$ respectively.
  - Implementation: Want to minimize the square of the distance from the points to the plane. The plane contains the centroid of the data ($x0, y0, z0$) and its normal vector is the singular vector of M corresponding to the smallest singular value where M is given by,

$$M = \begin{bmatrix} x1-x0 & y1-y0 & z1-z0 \\ x2-x0 & y2-y0 & z2-z0 \\ . & . & . \\ . & . & . \\ xn-x0 & yn-y0 & zn-z0 \end{bmatrix}$$

  - Output: Coefficients a_0, a_1 and a_2 such that $a_1x+a_2y+a_0=z$ and distance of each data point from the plane to calculate the *p-v* nonflatness
  - This is straightforward and is basically an eigenvalue problem but is different from the flatness definitions in SEMI P37 and P40.

Ref: C. M. Shakarji, ‘Least-squares fitting algorithms of the NIST algorithm testing system,” *J. Res. Natl. Inst. Stand. Technol.*, Vol. 103, No. 6, 1998, p. 641.

Description of Methods

- ***Minimax Method (Optimization)***
  - **Input: x, y, z data**
  - **Implementation: Want to minimize the maximum distance from the points to the plane, given by,**

$$d = \frac{|a1x + a2y + a0|}{\sqrt{a1^2 + a2^2}}$$

  - **This is done using the 'fminimax' function in MATLAB® and the algorithm developed by Anderson, Osborne and Watson (see Ref. below)**
  - **Output: Coefficients a_0, a_1 and a_2 such that $a_1x+a_2y+a_0=z$ and distance of each data point from the plane to calculate the *p-v* flatness**
  - **This problem falls into the realm of optimization because of the absolute value in the distance equation (the square root can be eliminated with a simple transformation of parameters). This makes it time consuming and convergence to global optima is not guaranteed. This is the plane used in the flatness definitions in the SEMI standards.**

Ref: G. A. Watson, "On an algorithm for nonlinear minimax approximation," *Numerical Mathematics*, Vol. 13, No. 3, 1970, pp. 160-162.

Comparison of Methods

Substrate Number	Substrate Name and Surface	Zygo Fit *p-v* (nm)	LS Fit *p-v* (nm)	MM Fit *p-v* (nm)	Zygo vs LS (%)	LS vs MM (%)	Zygo vs MM (%)
1	Box-1 Slot-1 Backside	1094	1084	963	0.9	12.6	13.6
1	Box-1 Slot-1 Frontside	882	858	762	2.8	12.6	15.7
2	Box-1 Slot-2 Backside	449	414	404	8.5	2.5	11.1
2	Box-1 Slot-2 Frontside	588	549	518	7.1	6.0	13.5
3	Box-1 Slot-3 Backside	1568	1486	1425	5.5	4.3	10.0
3	Box-1 Slot-3 Frontside	1043	994	926	4.9	7.3	12.6
4	Box-1 Slot-4 Backside	682	677	650	0.7	4.2	4.9
4	Box-1 Slot-4 Frontside	432	426	401	1.4	6.2	7.7
5	Box-1 Slot-5 Backside	638	628	550	1.6	14.2	16.0
5	Box-1 Slot-5 Frontside	585	578	517	1.2	11.8	13.2
6	Box-1 Slot-6 Backside	765	757	739	1.1	2.4	3.5
6	Box-1 Slot-6 Frontside	558	551	542	1.3	1.7	3.0

LS: Least Squares Method

MM: Minimax Method

Comparison of Methods (continued)

Substrate Number	Substrate Name and Surface	Zygo Fit *p-v* (nm)	LS Fit *p-v* (nm)	MM Fit *p-v* (nm)	Zygo vs LS (%)	LS vs MM (%)	Zygo vs MM (%)
7	Box-1 Slot-7 Backside	1622	1584	1442	2.4	9.8	12.5
7	Box-1 Slot-7 Frontside	870	862	806	0.9	6.9	7.9
8	Box-2 Slot-1 Backside	1597	1552	1454	2.9	6.7	9.8
8	Box-2 Slot-1 Frontside	833	687	624	21.3	10.1	33.5
9	Box-2 Slot-2 Backside	1056	838	804	26.0	4.2	31.3
9	Box-2 Slot-2 Frontside	1816	1205	1113	50.7	8.3	63.2
10	Box-2 Slot-3 Backside	1142	753	711	51.7	5.9	60.6
10	Box-2 Slot-3 Frontside	1898	1288	1179	47.4	9.2	61.0
11	Box-2 Slot-4 Backside	1264	836	754	51.2	10.9	67.6
11	Box-2 Slot-4 Frontside	1765	1194	1116	47.8	7.0	58.2
12	Box-2 Slot-5 Backside	1312	873	764	50.3	14.3	71.7
12	Box-2 Slot-5 Frontside	1683	1577	1541	6.7	2.3	9.2

LS: Least Squares Method

MM: Minimax Method

Comments on the Flatness Definition

- **SEMI P-37 and P-40 indicate that the Minimax Method should be used to determine the Best Fit Plane.**
- **The Minimax Method is more difficult to apply, and convergence to global optima is not always guaranteed.**
- **The Least Squares Method is used in the standards for wafer flatness.**

- **Should SEMI P-37 and P-40 be changed to require that the Least Squares Method be used to determine the Best Fit Plane?**

Satisfying SEMI P40

SEMI P40 Flatness Requirements

Table 1 Flatness of the mounting surface

Any square region with specified edge length (millimeters)	*Peak-to-valley flatness (nanometers)*
150	48
75	24
40	12
25	8
20	6
10	3

- **From Scott Hector:**

  The flatness error variance is the integral under the PSD curve. The rms flatness error over a band of spatial wavelengths is the square root of the integral under the PSD curve. Assume that peak-to-valley flatness error is 6 times the rms value. You can construct a PSD (it will be piecewise linear) from the table in P40. That "ideal" PSD can be compared against actual measured PSD plots.

- **How do we implement this SEMI P-40 requirement?**