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Design and Verification of a High Load Large Flexure Hinge Stage for Nanometer Displacement

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Abstract:
Measuring nanometer geometric structure size on large dimensional wafer needs large stage to carry wafer with nanometer displacements. For large stage, the heavy weight makes it difficult to attain nanometer steps. In the article, a high load two-dimensional precision stage with nanometer resolution utilizing piezoelectric stick actuators and a novel superimposed circular flexure hinge chain structure is researched. The stage is designed to achieve high payload, nanometer displacement and low coupling errors. The verification of working stiffness, coupling stiffness, coupling coefficient as well as hinge stress shows the performance have very good consistency with calculation.

Keywords:
Nanometer stage; Circular flexure hinge; Superimposed hinge chain; Stiffness; Coupling;

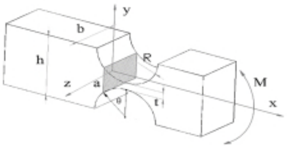
1. Introduction

In semiconductor manufacturing area, It is great challenge for carrying 8 inch and above wafer to move with nanometer steps when measuring the critical dimension structure size on wafer [1][2]. So the stage must possess large size, high payload and nanometer resolution at the same time [3][4][5][6]. In response to these rigid requirements, the novel stage superimposes flexure hinge and link rod in a specific way to achieve long displacement range and nanometer resolution; three piezoelectric actuator are also utilized to driven the stage and compensate rotation. In design the parameters are precisely calculated to keep stage has good range, resolution and suitable stress, besides this, it should avoid aggravate coupling displacements.

Before, some researcher had made theory research of flexure hinge[7][8], Niaritsiry[9], Smith[10] and Paros[11] had researched flexure hinge's errors sources, rotation compiling coefficients and stiffness, these work are impressive, but there still have many aspects need to be studied in construction of an integral large size flexure hinge stage[12][13]. This is the article's purpose.

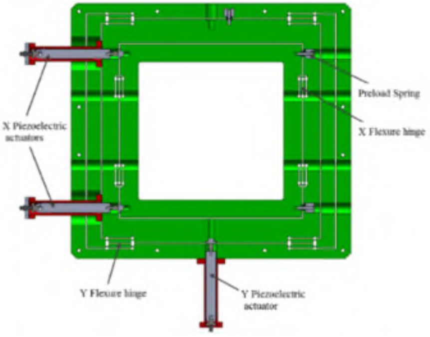
2. Nanometer stage design

Flexure hinge shows like Fig 1(a), includes width b, radius R, the min thickness t and height h. If there is a torque M, the thin part t will rotate around an axis, when M disappears, the elastic deformation disappears. In design, the single superimposed flexure hinge shows in Fig 1(b), L is the hinge's length, d is the distance between adjacent hinges. The superimposed flexure hinge can form a chain structure has only one half stress of the parallelogram link rod.



a. basic structure of flexure hinge

b. superimposed circular flexure hinge chain



c. schematic of nanometer stage

Figure 1. (the structure of flexure hinge and nanometer stage)

The stage in Fig 1(c) includes piezoelectric stick actuators and stage with outer, middle and inner nested hollow frames, each adjacent frames are connected by flexure hinge chains. Among them, the outer frame is fixed, the middle and inner frames can respectively move along X and Y axis orthogonally with nanometer resolution. In order to eliminate lost motion and contact deformation errors, there are extra springs mounted on the opposite side of the actuators to offer preload.

3. Finite Element Analysis Verification

In order to examine the correctness of results and optimize the parameters, FE analysis software is used to simulate deformations and stresses induced by fixed payload[16]. Table 1 lists stage geometric parameters, to verify the reliability of derived equation, theses parameters are utilized to build tetrahedron and hexahedron mesh net of mechanical stage, especially in places where stress concentration exists, the finer net mesh is employed. The net mesh of stage is in Fig 2(a).

Table 1. (Geometric parameters of superimposed flexure hinge)

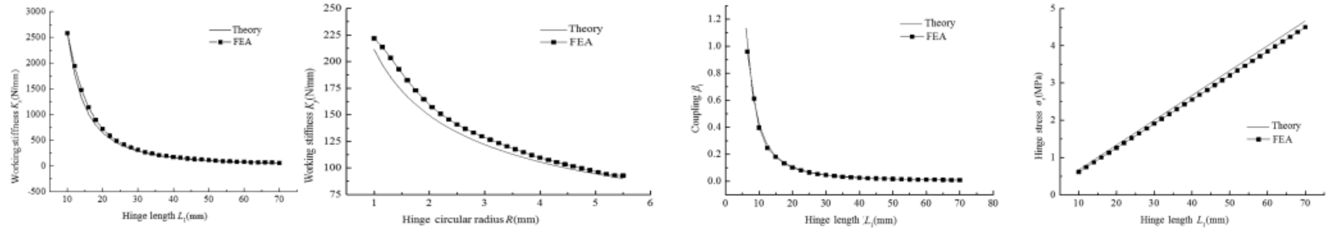
Elastic modulus E (N/m^2)	Poisson ratio	Radius R (mm)	Width b (mm)	Thickness T (mm)	L_1 (mm)	L_2 (mm)	d_1 (mm)	d_2 (mm)
1.986×10^{11}	0.26	3	45	0.5	33	46	6.5	7.5

Table 2. Deviation between theory calculation and simulation

	X stiffness K_x (N/mm)	X coupling stiffness K_{coupling} (N/mm)	Y stiffness K_y (N/mm)	Y coupling stiffness K_{coupling} (N/mm)	100μm inner displacementstress(Mpa)	100μm middle displacement stress (Mpa)
Calculation	236.99	6108.39	121.97	4588.08	52.14	37.40
Simulation	253.34	5803.83	130.58	4345.91	51.265	37.05
Deviation (%)	6.90	4.92	7.06	5.30	1.67	0.94

Table 2 lists the calculation and simulation values of stage's characteristic parameters under the condition in Table 1. It is showed that when fixed out frame, let middle frame is pushed by $2F_{\text{middle}}=10N$, inner frame is pushed by $F_{\text{inner}}=10N$, coupling force $F_{\text{middle coupling}}=F_{\text{inner compling}}=1N$, compared results between calculation and simulations, the deviation is within 7.06%. In order to further examine the equations, different working stiffness K_x, K_y, coupling coefficient β and flexure hinge stress σ_x are calculated by change flexure hinge length $L1$, $L2$ and radius R, which are then verified with FE simulation, the results are plotted in Fig 3(a), (b), (c), (d).

In Fig 3(a), both theory and FE analysis show the working stiffness is inversely proportional to L_1 length, when $F_{\text{inner}}=1N$, the maximum deviation appears at $L_1=17.5$, the deviation value is 7.13%; the minimum deviation appears at $L_1=17.5$, the value is 1.03%.



(a) relation between K_x and L_1 (b) relation between K_y and R (c) relation between β_1 and L_1 (d) relation between σ_1 and L_1

Figure 2. (theory and FE analysis cross verification)

In Fig 3(b), theory shows stiffness K_y is inversely proportional to length L_2 and R, the maximum deviation appears at $R=1.4$, the deviation value is 11.2%; the minimum deviation appears at $L_1=5.4$, the value is 2.1%.

In Fig 3(c), both theory and FE analysis show that coupling coefficient β is inversely proportional to flexure hinge length L, when $F_{\text{inner}}=1N$, $F_{\text{inner compling}}=1N$, the maximum deviation appears at $L_1=12$, the deviation value is 6.4% the minimum deviation appears at $L_1=56$, the value is 3.2%.

In Fig 3(d) shows flexure hinge stress σ_x is proportional to hinge length, the max deviation between theory and FE analysis appears at $L_1=70$ with deviation value 4.2%, the minimum appears at $L_1=13$ with value 1.03%.

It can be seen theory equation and FE analysis approach each other very well, the deviation is small, and the reason of deviation is that 1. The theory equation builds model based on pseudo rigid body approximation, which makes certain simplification; 2. The accuracy of simulation is limited by FE net mesh method and calculation convergence precision, which arises errors; 3. The flexure hinge rotation stiffness equation also has some simplifications.

To summarize the results, it shows:

1. To enhance the displacement range, the stiffness K must be as small as possible, this can be attained by adding hinge length L, radius R and reducing t.
2. In order to reduce coupling coefficient β to as small as possible, the hinge length L must be large, distance between adjacent hinges d must be small.
3. In order to keep flexure hinge's concentration stress beneath the maximum permissible stress, when push force is fixed, the hinge length L should be as short as possible, thinnest part t should be as large as possible.

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