Modeling and Control of Nanomirrors for EUV Maskless Lithography

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ABSTRACT

The design of mirrors for use in EUV maskless lithography is presented in this paper. We propose a novel nanomirror system with a linear comb actuator, which has favorable stability and performance. A bias voltage and resistor are provided to introduce electrical damping while a modulation voltage turns on/off the nanomirror.

The issue of transient optimization to minimize the settling time and overshoot of time response is discussed. Two important control parameters are obtained which lead to specification of an optimal resistor and operating position.

Keywords: EUV maskless lithography, nanomirror, comb actuator, overshoot, settling time, Routh-Hurwitz criterion.

1 INTRODUCTION

Extreme-Ultraviolet Lithography (EUVL) is under development as a contender for post-DUV lithography in the 100nm feature-size regime. For cost and defect control reasons there is an incentive to replace physical masks with an electronic equivalent, and the present research is aimed at using an array of modulatable mirrors as an electronic mask [1]. Fig. 1 is a cartoon of an almost-conventional EUV system, but with a mirror array in place of the mask.

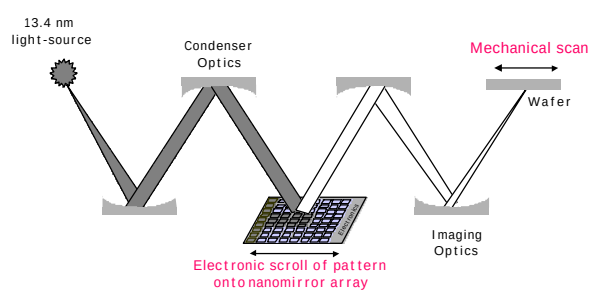
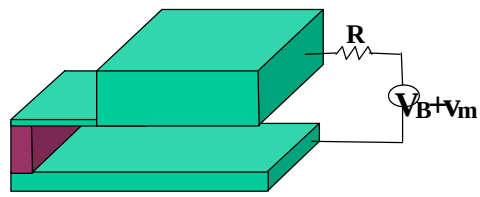
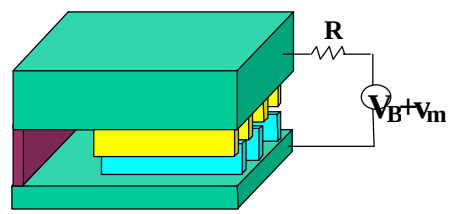


Figure 1. Direct pattern generation using a nanomirror array as electronic mask.

The optical operation of the nanomirror array is similar to the familiar Digital Micromirror Devices (DMD) from Texas Instruments wherein individual pixels are modulated by selectively deflecting mirrors in the array [2]. However, EUV nanomirrors in comparison to DMDs are much smaller in size ($\leq 1mm^2$), operate at a higher frequency, and are position-controlled by a different mechanism. A simple flexure-supported parallel-plate mirror (Fig. 2(a)) is based on the attractive electrostatic force across the mirror gap resisted by the flexure spring. The very small forces available for motion and the need to operate in vacuum preclude hard stop (and pull-in) as well as squeeze-film damping; thus we have chosen to use electrical damping. For this purpose, a bias voltage and a resistor are provided as shown in Fig. 2. (The resistor is built into the flexure).



(a) Parallel-plate structure.



(b) Comb-actuator structure.

Figure 2. Comparison of the structure of two different electrostatic actuators (not to scale). A bias voltage V_B provides a charge that introduces electrical damping. The small-signal v_m modulates the mirror tilt (about 1/2 degree provides full on-off modulation in the present design).

2 TRANSIENT OPTIMIZATION

Dynamic analysis of mirror vibration, carried out by combining force, moment and electric loop equations, shows that the damped parallel-plate structure of Fig. 2(a) is fundamentally unstable. Fig 2(b) shows a modified mirror with a comb drive that avoids such instability by providing a linear actuator. A vertical flexure hidden underneath the nanomirror further improves the performance by suppressing one vibrational mode and permits a denser mirror array. The electric and moment equations are:

$$V_B + v_m = i\,R + V = \frac{dq}{dt}R + \frac{q}{C} \qquad (1)$$

$$I_{mirror}\frac{d^2q}{dt^2} = M_{beam} + M_{electric} = -kq + \frac{1}{2}V^2\frac{\partial C}{\partial q} \qquad (2)$$

where q is the tilt angle of mirror ($q < 0$), I_{mirror} is the mass moment of inertia and k is the rotational spring constant. We assume that each state variable can be composed of an equilibrium value plus a small perturbation:

$$q = Q_0 + q_1, \boldsymbol{q} = \boldsymbol{q}_0 + \boldsymbol{q}_1 \tag{3}$$

These equations can be linearized and solved analytically by the perturbation method. The equilibrium state with a bias voltage is described by the following equations:

$$V_B = \frac{Q_0}{C_0}, C_0 \approx \frac{N(H - \frac{w}{2}\boldsymbol{q}_0)w}{G}, \frac{1}{2}V_B^2 \frac{\partial C}{\partial q} = k\boldsymbol{q}_0 \tag{4}$$

Here H is the initial overlap distance (without bias) between top and bottom combs, w is the width/length of a square mirror, N is the number of finger capacitor with a single gap, G is the gap distance between neighbor fingers. Obviously, mechanical damping in vacuum is ignored. The capacitance formula in (4) does not include the fringe effect, and some small geometrical errors are ignored. Substituting (3) into (1) and (2), subtracting the equilibrium equations of (4) and neglecting the products of small terms yield the normalized time response of tilt angle (in the Laplace domain with $w_0 t$ as the normalized time coordinate) to a step modulation:

$$Y(s) = \mathbf{L}[q_1(t)] = \frac{1}{s}\frac{1-E}{T}\frac{1}{s^3 + s^2/T + s + (1-E)/T} \tag{5}$$

where two control parameters are defined as:

$$T = RC_0 w_0, \; E = \frac{\frac{1}{2}V_B^2 C_0 \boldsymbol{h}}{\frac{1}{2}k\boldsymbol{q}_0^2 + \frac{1}{2}V_B^2 C_0 \boldsymbol{h}}. \tag{6}$$

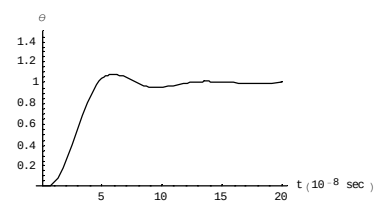
Here $w_0 = \sqrt{[k + \frac{V_B^2}{C_0}(\frac{\partial C}{\partial q})^2]/I_{mirror}}$ is the undamped natural frequency and $\boldsymbol{h} = (\frac{\partial C}{\partial q}\boldsymbol{q}_0 / C_0)^2$ represents the energy transfer efficiency of the actuator. The physical meaning of T is the electric/mechanical time constant ratio, and E is the release/storage energy ratio. It is evident from (6) that $E < 1$, thus Routh-Hurwitz stability criterion is satisfied and the dynamic system is stable. Combination of equation (4) and (6) gives another formula for E:

$$E = \frac{1}{1 + \frac{1}{2}(1 - \frac{2H}{w\boldsymbol{q}_0})} \tag{7}$$

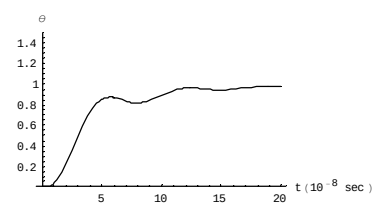
Since $\boldsymbol{q}_0$ is negative, E and energy transfer efficiency $\boldsymbol{h}$ are maximum when $H = 0$,

$$E_{max} = \frac{2}{3}, \text{ and } \boldsymbol{h}_{max} = 1 \tag{8}$$

Equation (8) is important for optimal design of a comb drive as it says that the initial overlap distance between fingers should be zero to get the maximum E and energy transfer efficiency $\boldsymbol{h}$. Based on this limitation of E, an optimization to minimize the settling time and overshoot using above parameters is completed and the optimal behavior is shown in Fig. 3(a), which requires about 20 M-ohm of resistance and initial zero comb overlap for a typical designed structure. The 50-nanosecond rise-time suggests 10-MHz operation. Numerical simulation of the response, Fig. 3(b) confirms the validity of our analytic optimization technique. The small difference between the approximate analysis and simulation may be due to the fact that we chose $V_B = 1.5\,V$ and $v_m = 0.5\,V$ for the purpose of low power operation which is required to achieve full combination of MEMS and MOS devices, and the assumption of much smaller modulation (perturbation) is only approximately satisfied.



(a) Using perturbation method.



(b) Using numerical simulation.

Figure 3. The optimal (normalized) time response of a typical comb-actuated mirror ($1mm$ on a side, $2V$ actuation voltage, 1 degree tilt). Here, $T = 9/10, E = 2/3$, $k = 2.53\times10^{-12}(N\cdot M), I_{mirror} = 4.85\times10^{-28}(Kg\cdot M^2)$.
(a) According to the analytic approximation and (b) by simulation.

3 CONCLUSION

A mirror structure is proposed which has superior performance and stability in comparison to the parallel-plate structure. Transient optimization of the dynamic system has been carried out and an optimal resistor has been obtained. A zero initial comb overlap is also required.

Numerical simulation is performed to confirm the validity of our analytic optimization technique.

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