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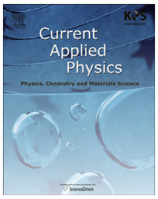

Impact of process parameters on pattern formation in the maskless plasmonic computational lithography

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ABSTRACT

The extraordinary optical transmission through a sub-wavelength size metal-aperture and metamaterials has been tremendous interests for the untilization of the surface plasmon polariton (SPP). Its technology, however, is hard to apply for the optical lithography process. In this study, a maskless plasmonic lithography (MPL) is modeled and simulated for 15-nm critical dimension (CD). The near-field intensity with the plasmonic phenomena of aperture shapes is described due to aperture parameters by using a scattering matrix (S-matrix) analysis method and the finite difference time domain (FDTD) method. MPL parameters of bowtie structures are optimized and improved for the imperfection of the resist pattern. The most dominant parameter on CD is gap size of bowtie by Taguchi method.

1. Introduction

Lithography technology has been developing the semiconductor industry according to Moore's law over 40 years. The current immersion ArF lithography locates at the crossroads of a decision on the next generation lithography (NGL) technology in terms of the improved limit of exposure wavelength and numerical aperture (NA) in Rayleigh's equation ($HP = k_1 \times \lambda/NA$). As a favorite successor of the immersion ArF lithography, extreme ultraviolet (EUV) lithography has been researching for 1 × nm technology nodes. X-ray lithography and the massively parallel e-beam lithography cannot provide effective cost for mass production. Multiple patterning such as quadruple patterning is confronted with the huge increase of cost of ownership (CoO) and overlay difficulty. Under such conditions, the high transmission through a sub-wavelength size metal-aperture has been tremendous interests for the maskless plasmonic lithography (MPL) [1,2]. The physical origin of this enhanced transmission is the excitation of surface plasmon polariton (SPP), which is the coupled mode excitation of an electromagnetic wave and free charges on a metal surface. MPL has advantages for low cost, the high-intensity nanometer-scale light spot beyond diffraction limit, and applicability of conventional light sources and resist materials [3,4]. To extend the scope of practical applications for SPP, MPL needs to be rigorously analyzed to ensure that it satisfies the demands of the semiconductor industry in terms of its ultimate resolution, pattern depth, overlay, and throughput. In this study, MPL process is modeled and simulated for 15-nm critical dimension (CD). The impact of process parameters on pattern formation is described to understand the effects of the pattern formation and optimize process parameters.

2. Maskless plasmonic lithography

MPL in Fig. 1 includes maskless plasmonic illumination (wavelength, aperture shapes, and thickness), prebake (time and temperature), exposure (Dill parameters (A, B, and C) and dose), post-exposure bake (PEB) (diffusion coefficient, time, and temperature), and development (rate function time and surface inhibitor), as shown in Table 1 [5–7]. Plasmonic illumination is performed by using an S-matrix analysis method and the FDTD method [8–11]. For resist flow of spin-coating, level-set method and a relative equation of Navier–Stokes equation are, respectively,

$$D_t\phi(x,t) + (1 - b\kappa(x,t))\|\nabla\phi(x,t)\| = 0, \quad (1)$$

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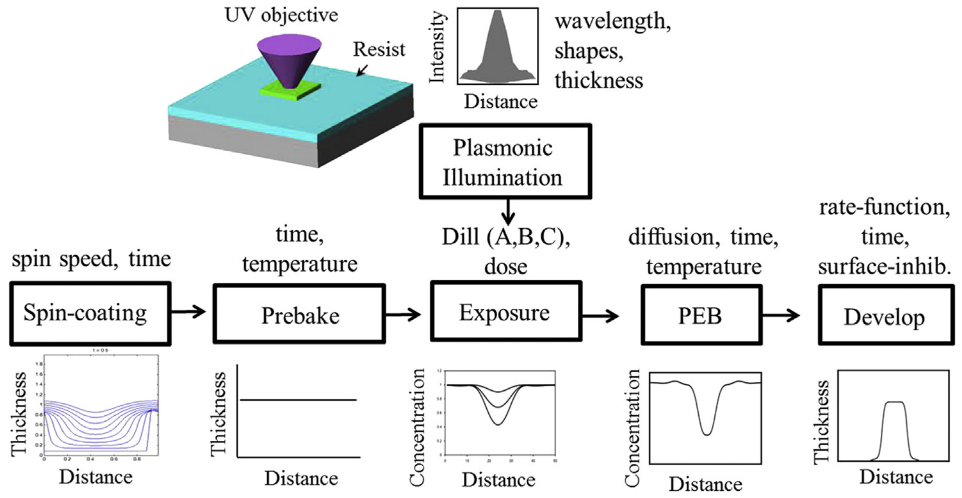

Fig. 1. Schematic flow of maskless plasmonic lithography: spin-coating, prebake, plasmonic illumination, exposure, post-exposure bake, and development.

$$\left(\frac{\partial^3 H}{\partial X^3}+\frac{\partial^3 S}{\partial X^3}\right)H^3+\Omega^2 H^3=\Omega^2, \tag{2}$$

where $\phi(t)$ is a level-set function, $\kappa(t)$ is mean curvature, b is constant value, and H, S, and Ω are dimensionless parameters [6,7]. For the sovent evaporation-diffusion of prebake, the concentration rate (M) after bake can be determined from.

$$\frac{dM}{dt}=-k_{evap}\cdot M, \quad k_{evap}=A_r e^{-E_a/k_b T}, \tag{3}$$

where k_{evap} is evaporation rate constant, A_r is Arrhenius coefficient, E_a is activation energy, k_b is Boltzmann constant, and T is absolute temperature. For exposure model, the reaction of intensity and photoactive compound [PAC] is determined by.

Table 1
MPL parameters of 15-nm pattern formation.

- **Source**
  Type: Gaussian Pulse, Polarization: x-direction,
  Amplitude (V/m): 1, Central wavelength (nm): 800, 365, and 248,
  Temporal width (fs): 2,
  Duration of Gaussian Source (No. of widths): 10.
- **Structure parameters**
  Layer 1: 50-nm, dielectric constant: 2.2,
  properties: Insulator,
  Layer 2: 24-nm, properties: Gold, (Bowtie Geometry) Triangle altitude: 20,
  Radius of Curvature: 10, Thickness: 24, Gap size: 10,
  Layer 3: 50-nm, dielectric constant: 2, properties: Insulator.
- **Prebake**
  Temperature: 90 °C, Warmup Time: 1 s
  Prebake Time: 60 s, LN Arrhenius: 40.89 1/min.
  Activation Energy: 34.32 kcal/mol,
- **Exposure parameters**
  Exposure Dose: 20 mJ/cm^2,
  A: 0.01 1/μm, B: 0.3 1/μm, C: 0.01 cm^2/mJ.
- **Post-exposure baking parameters**
  Diffusion length: 0.035 μm,
  Temperature: 100 °C,
  Time: 80 s, Exponent n: 2,
  Resist type: Positive.
- **Development parameters**
  Development Model: Mack model,
  R$_{min}$: 6.5 × 10^{-5} nm/s, R$_{max}$: 0.1 μm/s, n: 0.01,
  M$_{th}$: 0.36, time: 50 s.
- **2D resist profile**
  Contact hole: 15-nm, average sidewall angle: 70.32°.

$$\frac{\partial I}{\partial z}=-\alpha I, \quad \frac{d[PAC]}{dt}=-C\cdot[PAC]\cdot I, \tag{4}$$

where α $(=A[PAC]+B)$ is the optical absorption coefficient and A, B, and C are Dill's parameters [7]. For PEB model, the acid diffusion equation of the non-chemically-amplified resist (non-CAR) is

$$\frac{dM}{dt}=D_H\left(\frac{\partial^2 M}{\partial x^2}+\frac{\partial^2 M}{\partial y^2}\right), \tag{5}$$

where M is dissolution inhibitor (or PAC) and D_H is the acid diffusion coefficient [6,7]. For development model, Mack model and raytrancing model are, respectively,

$$R(M)=R_{max}\frac{(a+1)(1-M)^n}{a+(1-M)^n}+R_{min}, \quad a=\frac{(n+1)}{(n-1)}(1-M_{th})^n, \tag{6}$$

$$P_n(x,y,z)=P_{n-1}(x,y,z)+\widehat{S}_{n-1}(x,y,z)R_{n-1}(x,y,z)\Delta t, \tag{7}$$

where $R(M)$ is development rate, R_{max} (or R_{min}) is the maximum (or minimum) development rate, M_{th} is the threshold inhibitor concentration, n is the reaction order, $\widehat{S}_n$ is the unit vector of the trace direction, P_n is ray position, and R_n is the surface evolution rate [6,7]. The imperfection of resist pattern is possibly attributed to the imperfect of aperture structure and the roughness of the metal surface, so that this resist pattern can be further improved by optimizing lithography conditions.

3. Analysis and discussion

SPP transmittance is calculated at 1-nm distance from the bottom of a gold layer by using an S-matrix analysis method [8,9]. For transmittance spectrum of a 100-nm gold thickness due to hole's radiuses in Fig. 2(a), the localized surface plasmon resonance (LSPR) shifts to lower energy when hole's radius becomes smaller, as same as Ref. [12,13]. LSPR positions in Fig. 2(b) are affected by the orders of fractal patterns. For the increasing orders, the intensity enhancement becomes larger and has a spot position. In simulation conditions of 100-nm a-width, 100-nm gold thickness, and incident light with 60° angle to surface in Fig. 2(c), LSPR shifts to lower