# Deterministic Fabrication of Nanostructures in Plasmonic Lens by Focused Ion Beam (FIB)

J. Sun[1], X. Luo[1], J. Ritchie[1], W. Chang[1] and W. Wang[1]
[1]*School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, EH14 4AS, UK*

*X.Luo@hw.ac.uk*

## Abstract

Focused ion beam (FIB) machining is a powerful technique for micro/nanofabrication of optics. In this paper, a highly robust and accurate computational technique based on level set method is developed for precisely and deterministically fabrication of nanodots for far field plasmonic lens by FIB. Effectiveness of the simulation approach has been demonstrated through FIB fabrication of two nanodots.

## 1 Introduction

FIB machining is a powerful technique for micro/nanofabrication of optics. It uses focused beam of ions to form functional micro/nanostructures through material removal or deposition with nanometer precision on almost any solid materials. Current FIB systems are able to produce a beam size smaller than 3.5 nm with an excellent beam-positioning accuracy and stable operating condition. Therefore, it can be used to fabricate structures such as nanometer-sized periodic dots to couple free space light into surface plasmons in a far field plasmonic lens. Research shows that metal films perforated with a periodic array of subwavelength holes can enhanced light transmission at selected wavelengths[1]. The nanodots' diameter should be small enough to ensure that no propagating modes can be supported at the wavelengths of interest. The depth of the nanodots affects the intensity of transmission light intensely. Precisely and deterministically fabrication of these nanostructures are therefore essential for the plasmonic lens to offer perfect optical images beyond the classical Abbe diffraction limit for bio-imaging and nanolithography applications. However, the fabrication accuracy of these nanodots can be greatly degraded due to ions redeposition in the FIB milling process. The redeposition is caused by secondary scattered atoms which are knocked out by the incident ion beam. Some of these scattered atoms can stick to the machined surface which will cause the machined surface diverge from the shape intended. On the other hand the fabrication process of these nanostructures in plasmonic lens is complex and expensive. It is very important for physicists to have access to predictable and optimized geometries before fabricate them. In order to develop a deterministic FIB fabrication process we propose a Monte Carlo method to determine the sputtering rate (the number of atoms ejected per incident ion) of atoms. Also we apply level set method[2] to track the generation of surface topography by taking into account of redeposition effect. In this method, the moving front is viewed as a particular level set of a higher-dimensional function (level set function). The surface topological merging and breaking, sharp gradients and cusps can be easily handled. In addition, the effects of curvature can be incorporated as well, which make this method much more robust than other surface topography simulation methods.

## 2 Surface topography model

The evolution of the nanodots' surface topography evolution can be regarded as a certain distribution of velocity field. So firstly we need calculate the normal velocities of each point on the substrate surface. The velocity $v_{\square}(x)$ is proportional to the total fluxes at point $x$ on the machined surface. It can be calculated by using the total surface fluxes model proposed by H.Kim *et al.*[3] The total flux ($F_{total}$) at each point on the surface includes the totla flux of sputtered atoms ($F_{direct}$) and the total flux of redeposition atoms ($F_{indirect}$), which can be described as:

$$F_{total} = F_{direct} + F_{indirect}$$

$$F_{direct} = F_{incident} Y(\theta)\cos(\theta)$$

$$F_{indirect} = -S_c \int \frac{F_{direct} f(\alpha)\cos(\beta)}{d^2 * \iint f(\alpha)\, d\alpha\, d\varphi} dA$$

where $Y(\theta)$ is the angular dependance of sputter yield, $S_c$ is the sticking coefficient, $f(\alpha)$ is angular distribution of the sputtered atoms, and $\varphi$ is the rotational angle. The surface generation mechanism can then be shown in Figure 1. The central mathematical idea of level set method is to view the moving front as a particular level set of a higher dimensional level set function $\phi(x,t)$ . The evolution of the level set function is charactericed by the velocities $v_{\square}$ which is perpendicular to the surface. The generated surface at a certain time *t* is then determined by solving time-dependent Hamilton–Jacobi equation in the form of:

$$\phi_t(x,t) - v_{\perp}(x,t)\left|\nabla\phi(x,t)\right| = 0 \qquad \phi(x,t=0) = \Gamma$$

where Γ is a signed distance function. It stands for the distance from the point *x* to the machined surface , with a positive (negative) sign if the point is outside (inside) the surface. The moving front is the data set of the points exactly on the surface. As it is corresponding to Γ=0, it is also called the zero level set of the level set function. Forward Euler time discretization and upwind spatial differencing is used as a robust way to solve the hyperbolic level set equation. When we implement level set method in the ion beam simulation model, three dimensional reconstruction is applied based on the geometric symmetry of nanodot. Finally a quasi three dimensional simulation program based on level set method is developed for FIB nano fabrication.

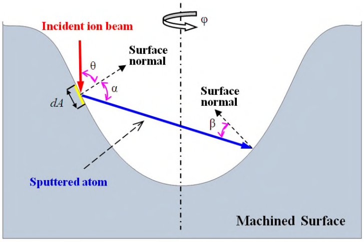
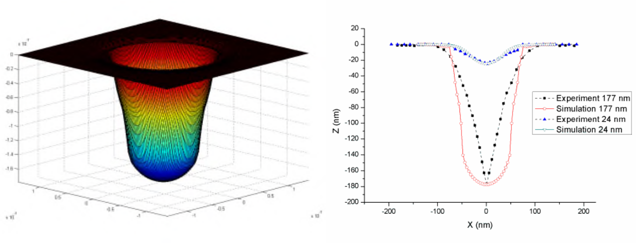


Figure 1: Schematic illustration of the generation mechanism of machined surface by ion beam machining

## 3 Results and discussions

Figure 2 shows simulation and experimental[4] results of two nanodots, which were fabricated under 50 keV gallium ion beam with a diameter of 68 nm. The dwell time was 0.011s and 0.111s respectively. The comparison between simulation and experiment in Figure 2 (b) shows that the milling depths are in good agreement at the bottom of the nanodots, with errors less than 1 nm. The narrow and sharp experimental contour with a depth of 177 nm was caused by the AFM due to limited sharpness of the AFM tip. It also shows that redeposition of atoms has significant effects on surface generation. The FIB milling depth and mouth width of nanodots both increase with dwell time nonlinearly in nano scale. Further study indicates that with the depth of a nanodot increases, the redeposition fluxes keep increasing until a convergence flux is formed, which achieve a balance between redeposition flux and incident flux in the end.



(a) (b)

Figure 2: Simulation results and the comparison with experiment. (a) Simulation result of a 3D nanodot; (b) Comparison of two nanodots (24nm and 177 nm in depth) with experiment.

## 4 Conclusion

In this paper a modelling approach has been developed to successfully simulate surface generation by FIB. This work provides helpful information for an actual FIB nano fabrication process. One can use this program to specify proper fabrication parameters for a designed nanodots array. To the authors' knowledge this is the first attempt to apply level set method to simulate three dimensional FIB topography generation. A fast marching method for building of extension velocity will be further developed in the future to improve the simulation efficency and obtain much smoother and more accurate evolving machined surface.

## References:

[1] Degiron, A., et al., Applied Physics Letters, **81**, 4327(2002).

[2] Sethian, J.A., Level Set Methods and Fast Marching Method. 1999: London: Cambridge University Press.

[3] Kim, H.B., et al., Nanotechnology, **18**, pp. 245303-245303(2007).

[4] Kim, H.B., et al., **17**, pp. 1178–1183(2007).