Nonlinear dynamic response of cantilever beam tip during atomic force microscopy (AFM) nanolithography of copper surface

Yen-Liang Yeh\textsuperscript{1}, Cheng-Chi Wang\textsuperscript{2}, Ming-Jyi Jang\textsuperscript{1}, Yen-Pin Lin\textsuperscript{3}, Kuang-Sheng Chen\textsuperscript{3}

\textsuperscript{1}Department of Mechanical Engineering, Far East University, Hsin-Shih, Tainan, Taiwan, ROC
\textsuperscript{2}Department of Automation and Control Engineering, Far East University, Hsin-Shih, Tainan, Taiwan, ROC
\textsuperscript{3}Gradate, Department of Mechanical Engineering, Far East University, Hsin-Shih, Tainan, Taiwan, ROC

E-mail: yehyl@cc.feu.edu.tw

Abstract. This paper investigates the nonlinear dynamic response of an atomic force microscope (AFM) cantilever beam tip during the nanolithography of a copper (Cu) surface using a high-depth feed. The dynamic motion of the tip is modeled using a combined approach based on Newton’s law and empirical observations. The cutting force is determined from experimental observations of the piling height on the Cu surface and the rotation angle of the cantilever beam tip. It is found that the piling height increases linearly with the cantilever beam carrier velocity. Furthermore, the cantilever beam tip is found to execute a saw tooth motion. Both this motion and the shear cutting force are nonlinear. The elastic modulus in the \textit{y} direction is variable. Finally, the velocity of the cantilever beam tip as it traverses the specimen surface has a discrete characteristic rather than a smooth, continuous profile.

1. Introduction

Nanotechnology has found extensive application in many industrial processes recently as a means of manipulating the bio-chemical and mechanical properties of a material’s surface. Due to the extremely small scales involved, the investigation of a material’s nano properties requires the use of specialized tools and techniques. Among the various techniques in common use, Atomic Force Microscopy (AFM) provides the means to measure the surface portrait of a material or to fabricate nano-scale components. In the latter case, the component is produced through the direct manipulation of the sample material’s surface by a tip attached to the AFM cantilever beam. Applying this technique to materials of differing properties enables the production of components with a wide range of applications. In 2002, Fang et al. [2] studied the effects of the scribing feed rate on the atomic-scale lithography process by performing 3-D molecular dynamics (MD) simulations. Using Cu as the sample and feed depths of less than 100 nm, the authors identified a positive correlation between the resultant force, the surface roughness and

\textsuperscript{1} To whom any correspondence should be addressed
the feed depths lower than 2.3 nm. In 2004, Fonseca et al. [5] studied the effect of the scanning velocity on the nanolithography process and reported that the depth of the lithographic pattern increases with an increasing applied normal force. The authors also observed that smaller scratch depths and widths were formed at higher scanning velocities. In the same year, Blach et al. [3] reported on the role played by elastic recovery and chain scission within the sample in the occurrence (or otherwise) of the “ploughing phenomenon”.

The studies described above provide an understanding of the effect of the scanning velocity on the nanolithography characteristics. However, the dynamic motion of the cantilever beam during the nanolithography process requires further clarification. In 1998, Shimizu et al. [1] analyzed the dynamic behavior of the cantilever beam through the integrated application of Newton’s Laws and MD simulations. In 2004, Chen et al. [4] used a similar approach to explore the slip-stick phenomenon at the cantilever beam tip. In general, both studies validated the use of Newton’s law in establishing a dynamic model of the cantilever beam.

This paper uses Newton’s Law and experimental observations to examine the nonlinear dynamic motion of the cantilever beam tip during high feed-depth nanolithography. The investigations focus specifically on the effect of the velocity on the piling height, the shear force and the cantilever displacement profile. The nanolithography process is conducted on a Cu surface using a test mask measuring $20 \mu m \times 20 \mu m$ and a scratch feed-depth of $1 \mu m$.

### 2. Theory

Although designed originally as a means of conducting surface measurements, AFM has also been applied as a nanolithography technique in recent years. The AFM dynamics are very complex, but can be simulated using a MD modeling method. However, the simulation process is complex, and therefore this paper analyzes the AFM nanolithography process using a mathematical model derived by using the mechanics, i.e. Jun Shimizu et al. [1]

The current analysis assumes that

1. The simulation of the AFM dynamics commences after the cantilever beam has moved to the preliminary depth in the z direction.
2. The simulations consider the force in the y direction only. Adopting these assumptions, the mechanics of the AFM cantilever beam tip can be modeled as shown in Fig.1.

![Figure 1. Free body diagram of cantilever beam tip.](image)

In AFM nanolithography, the cantilever beam tip experiences two external forces, namely a cutting force and an extruding force. The corresponding free body diagram is shown in Fig.1.

From Fig.1, the rotation angle can be derived as

$$\cos \phi = \frac{h - h_c}{h}$$

(1)
where \( h \) is the height of the cantilever beam tip, \( \phi \) is the rotation angle of the cantilever beam tip (torque angle) and \( h_c = h - h \cos \phi \).

The angle of rotation can be determined from the torque formula as follows:

\[
\phi = \frac{TL}{GJ}  
\]  

(2)

where \( T \) is the torque, \( L \) is the length of the cantilever beam, \( G \) is the shear modulus and \( J \) is the polarization inertia.

Referring to Fig.1, the torque can be derived as

\[
T = F_y \cdot h \cos \phi + F_z \cdot h \sin \phi  
\]  

(3)

As a result of assumption 2, the force in the \( z \) direction tends to zero (\( F_z = 0 \)), and hence equation (3) can be re-written as

\[
T = F_y \cdot h \cos \phi = F_y \cdot h \frac{h - h_c}{h} = F_y \cdot (h - h_c)  
\]  

(4)

Substituting equation (4) into equation (2), the rotation angle of the cantilever beam tip can be written as

\[
\phi = \frac{TL}{GJ} = \cos^{-1}\left(\frac{h - h_c}{h}\right) = \frac{F_y \cdot (h - h_c) \cdot L}{GJ}  
\]  

(5)

Rearranging, the cutting force \( (F_y) \) is therefore expressed as

\[
F_y = \frac{GJ}{(h - h_c) \cdot L} \cdot \cos^{-1}\left(\frac{h - h_c}{h}\right)  
\]  

(6)

Figure 2 shows the dynamic motion of the cantilever beam during nanolithography.

**Figure 2.** Free body diagram of cantilever beam during nanolithography.

Applying Newton’s Law, the dynamic motion of the cantilever beam is given by

\[
k_y (V_t - x) - F_y = m \ddot{x}  
\]  

(7)

\[
\ddot{x} = \frac{k}{m} (V_t - x) - \frac{F_y}{m}  
\]  

(8)

Substituting equation (6) into equation (8) yields
\[
\ddot{x} = \frac{k}{m} (Vt - x) - \left( \frac{GJ}{(h - h_c) \cdot L} \cdot \cos^{-1} \left( \frac{h - h_c}{h} \right) \right) / m,
\]

where \( h_c \) is the difference between the initial and current tip depths. Equation (9) indicates that \( h_c \) is dependent on the cutting velocity. Therefore, the slope of the piling height on the Cu sample is also dependent on the cutting velocity, i.e.

\[
S_c = \frac{dh_c}{dx} = K_v \cdot V
\]

From equation (10), it follows that

\[
h_c = S_c \cdot x.
\]

Substituting equation (11) into equation (9), the dynamic motion of the cantilever beam tip during nanolithography can be written as

\[
\ddot{x} = \frac{k}{m} (Vt - x) - \left( \frac{GJ}{(h - K_v \times V \times x) \cdot L} \cdot \cos^{-1} \left( \frac{h - K_v \times V \times x}{h} \right) \right) / m
\]

As shown, the cantilever beam tip has a nonlinear dynamic response. However, given a knowledge of the coefficients in equation (12), the solution to this nonlinear equation can be obtained by numerical means.

3. Results and Discussions

3.1. Nanolithography processing conditions

The current experiments were performed using a CPR-II AFM from Veeco/DI. The AFM was fitted with an NSC15/AIBS tapping-mode cantilever beam, as shown in Fig.3. Nanolithography was performed using a Cu specimen within a zone measuring 20 \( \mu \)m \times 20 \( \mu \)m \times 1 \( \mu \)m, as shown in Fig.4.

The test temperature was 25\(^\circ\)C and the experiments were performed at four different cutting velocities, namely 1 \( \mu \)m/s, 3 \( \mu \)m/s, 7 \( \mu \)m/s, and 9 \( \mu \)m/s.

| Figure 3. Cantilever beam in tapping mode. | Figure 4. Nanolithography zone. |

3.2. The experiment result
Figure 5 illustrates the cutting results obtained at a cutting velocity of $9 \, \mu m/s$. In this figure, $H$ represents the height difference between two determined points in the sample, $D$ is the horizontal distance between them and $A$ is the angle between an imaginary line drawn from one point to the other and the horizontal. In Fig. 5, the horizontal distance between the two points is $5.469 \, \mu m$, the height difference between them is $584.7 \, nm$, and the angle between the imaginary connecting line and the horizontal is $6.102^\circ$. Consequently, the gradient of the imaginary point-to-point line is $0.1069$. ($H/D=5469/584.7=0.1069$). Figures 6, 7 and 8 present the corresponding results for cutting velocities of $7 \, \mu m/s$, $3 \, \mu m/s$ and $1 \, \mu m/s$, respectively. Overall, Figs. 5 - 8 indicate that the piling height increases with an increasing cutting velocity. Table 1 summarizes the experimental results illustrated in the four figures.

From Table 1, it is seen that as the cutting velocity is increased, the gradient of the point-to-point line (referred to hereafter as the piling slope) also increases. The correlation between the two variables is illustrated graphically in Fig. 9. The experimental results indicate that the piling slope and cutting velocity have an approximately linear relationship. From a simple regressional analysis, the constant of proportionality ($K_c$) is determined to be 0.0272.

| Table 1 | Cutting velocity and corresponding piling slope results for Cu nanolithography at 25°C |
|---------|----------------------------------|
| Velocity ($\mu m/s$) | 9 | 7 | 3 | 1 |
| Height (nm) | 584.7 | 426.0 | 201.6 | 62.81 |
| Point-to-point distance ($\mu m$) | 5.469 | 7.031 | 7.813 | 4.297 |
| Point-to-point angle (degrees) | 6.102 | 3.467 | 1.478 | 0.8375 |
| Piling slope | 0.1069 | 0.0605 | 0.0258 | 0.0146 |
3.3. The simulation result

As described earlier, the dynamic motion of the cantilever beam during nanolithography can be described by solving Eq. 12 numerically. In the current study, the solution procedure was executed using the following parameter values:

\[ L = 125 \mu m \quad W = 35 \mu m \quad d = 4 \mu m \quad h = 20 \mu m \quad E = 137 e^9 N/m^2 = 137 e - 3 N/\mu m^2 \quad K_c = 0.272 S/\mu m \quad \nu = 0.24 \quad G = \frac{E}{2(1+\nu)} = 55.242 \times 10^{-3} N/\mu m^2 \quad J = I_x + I_y = \frac{Wd(W^2 + d^2)}{12} = 173740(\mu m)^4, \]

and a cantilever beam density of 2330 kg/m³ [5-6].

The simulations were conducted for a total period of 100 seconds with an interval of 0.01 seconds between successive sampling points. Figure 10 presents the numerical results obtained for the variation of the piling height with the tip displacement as a function of the cutting velocity. It is observed that the piling height increases with the cutting velocity. In this respect, the simulation results are consistent with the experimental findings presented in Figs. 5-8. Figure 11 describes the displacement of the cantilever beam tip over time. It is evident that the tip performs a non-linear motion. This trend is most likely attributed to the presence of slip-stick at the cantilever beam tip. Under static conditions, the shear force imposed by the tip on the Cu substrate is less than the limiting strength of Cu, and hence cutting does not take place. However, as the cantilever beam carrier traverses the substrate surface, the shear force experienced by the Cu substrate increases. At a certain point, the shear force exceeds the limiting strength of Cu, resulting in a cutting action. The resultant reduction in shear force again brings about a state in which the material’s limiting strength is dominant, and thus movement of the cantilever beam tip temporarily ceases. As a result, the displacement profile of the cantilever beam tip is likely to have a saw-tooth form. From Fig. 11, it can be inferred that the elastic modulus in the y direction \((k_y)\) is not constant, but increases with increasing \((Vt - x)\). The elastic property of the cantilever beam is therefore nonlinear.

Figure 12 shows the relationship between the shear cutting force and the displacement of the cantilever beam. The relationship is seen to be non-linear, which suggests that the shear cutting force also has a saw-tooth profile. Furthermore, for a given displacement, it is apparent that the shear cutting force increases as the velocity of the cantilever beam increases.
When a nonlinear shear cutting force is applied to the sample material, the motion of the cantilever beam tip is also nonlinear. The saw-tooth nature of the shear cutting force profile causes the cantilever beam tip velocity to have a pronounced discrete characteristic as it traverses the specimen surface, as shown in Fig. 13. It can be seen that the amplitude of the tip velocity vibration increases as the velocity of the cantilever beam carrier increases.

4. Conclusions
This paper has investigated the relationship between the cantilever beam tip motion and the cutting velocity during the nanolithography of a Cu surface. The results support the following conclusions:

An increased cantilever beam carrier velocity results in an increased piling height.

The variation of the cantilever beam displacement over time is nonlinear. The displacement profile of the cantilever beam tip is thought to have a saw-tooth form.

The relationship between the shear cutting force and the cantilever beam displacement is nonlinear and is also thought to have a saw-tooth characteristic.

The elastic modulus in the y direction $(k_y)$ increases with increasing $(Vt - x)$. The cantilever beam has a nonlinear elastic property.

The cantilever beam tip velocity has a pronounced discrete characteristic as the tip traverses the specimen surface.

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References

[1] Shimizu J, Hiroshi E, Yoritsune M and Ohmura E 1998 Nanotechnology 9 118
[2] Fang T H, Weng C I and Chang J G 2002 Surface Science 501 138
[3] Blach J A, Watson G S and Brown C L 2004 Thin Solid Films 459 95
[4] Chen C K, Chen B H and Yang Y T 2004, Nanotechnology 15 1771
[5] Fonseca Filho and Prioli R 2004 Materials science and Engineering B 112 194
[6] Yeh Y L and Wang C C2005 The 29 National Conference on Theoretical and Applied Mechanics