Fabrication and measurement of traceable pitch standard with a big area at trans-scale*

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Atom lithography with chromium can be utilized to fabricate a pitch standard, which is directly traceable to the wavelength of the laser standing waves. The result of a calibrated commercial AFM measurement demonstrates that the pitch standard is (212.8±0.1) nm with a peak-to-valley-height (PTVH) better than 20 nm. The measurement results show the high period accuracy of traceability with the standing laser wavelength ($\lambda/2 = 212.78$ nm). The Cr nano-grating covers a 1000 μm×500 μm area, with a PTVH better than 10 nm. The feature width broadening of the Cr nanostructure has been experimentally observed along the direction of the standing waves. The PTVH along the Gaussian laser direction is similar to a Gaussian distribution. Highly uniform periodic nanostructures with a big area at the millimeter scale, and the surface growth uniformity of the Cr nano-grating, show its great potential in the application of a traceable pitch standard at trans-scales.

Keywords: atom lithography, nano-scale metrology standard, traceability

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1. Introduction

It is critical to be able to fabricate an accurate traceable metrology transfer standard at the nano-scale in nanotechnology.[1] Atom lithography,[2,3] whose nano-grating is directly traceable to the standing laser wavelength, is an ideal nano-grating fabrication technology. As a pitch standard at the nanometer-scale, the nano-grating can substitute the laser interference technology for the calibration of scanning probe microscopes (SPM, AFM), scanning electron microscopes (SEM), and so on. Moreover, using a grating as a standard in the traceability chain can shorten the traceability chain and improve practical applications, with less errors brought in.

Atom lithography has been successfully demonstrated using Na,[4] Cr,[5,6] Al,[7] Yb,[8] and Fe[9] atoms deposited onto a substrate through a laser standing wave (SW) grazing across the surface. In addition, $\lambda/4$ (106.4 nm),[10] $\lambda/8$ (53.2 nm)[11] pitch standards and hexagonal nanostructures[6] have been generated by light marks for neutral Cr atoms. Recently, a structured mirror array[12] has been designed for the two-dimensional collimation of Cr beams. In addition, a double half Gaussian standing wave field[13] has also been generated for better deposition in an atom lithography experiment.[14] Nano-metrology is the science of the measurement of samples at a nano-scale level, and typical dimensions of nano-systems vary from 0.1 nm–100 nm.[1] Because the nano-grating covers a millimeter-sized area with a pitch at nano-scale, atom lithography can be used to fabricate traceable pitch standards at trans-scales, which are required for both micro-metrology and nano-metrology.

Because chromium (Cr) has low surface diffusion and high chemical stability,[5] which makes it suitable as an etch mask, we have chosen to use Cr as an ideal element for laser-focused atom deposition. In this paper, we present the fabrication process and measurement results of a calibrated commercial AFM. The distribution characteristics of the pitch standard show its great potential to be used as an available length calibration standard. In addition, some of the key issues in Cr atom lithography will be discussed.

2. Theories

The schematic of a one-dimensional laser focused Cr atomic deposition experiments is illustrated in Fig. 1.[15] When the collimated Cr atoms pass through a near-resonant laser light, grazing across the substrate surface, an induced dipole force on the atom interacts with the laser to impose a force toward the nodes or antinodes of the standing wave. Because the linear and inherent parallel pattern of deposited periodic nano-grating has a high accuracy with half of the laser wavelength, such a structure is ideal for the application as a calibration length standard in nanotechnology. In this paper, we call the optical axis direction the "standing wave direction", and the direction perpendicular to the optical axis

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and the atoms the "Gaussian direction" for the sake of convenience.

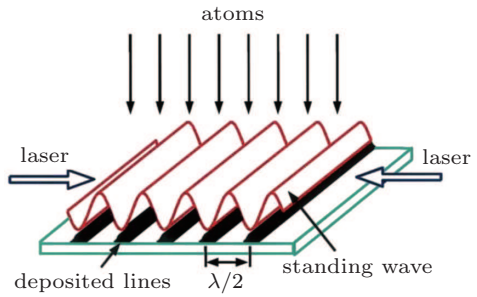


Fig. 1. (color online) The schematic of Cr atom lithography.

Quantum theory analysis indicates that the optical potential imposed on the ground state atoms is as given below[16]

$$U(x,y,z) = \frac{1}{2}\hbar\Delta \ln\left(1 + \frac{I(x,y,z)}{I_S}\frac{\Gamma^2}{4\Delta^2+\Gamma^2}\right), \qquad (1)$$

where $\hbar = h/2\pi$, h is the Planck constant, Δ is the laser detuning, Γ is the resonance line-width, I_S is the atomic saturation intensity, and $I(x,y,z)$ is the laser E-field amplitude. In the experiment, the laser wavelength is $\lambda = 425.55$ nm, which is strictly in correspondence with the ^{52}Cr atomic resonance transition: $^7S_3 \rightarrow {}^7P_4^0$. Therefore, a Cr nano-grating fabricated by atom lithography is directly traceable to the atom absolute transition frequency, and its pitch is $\lambda/2 = 212.78$ nm, which is ideal for nano-metrology standards.

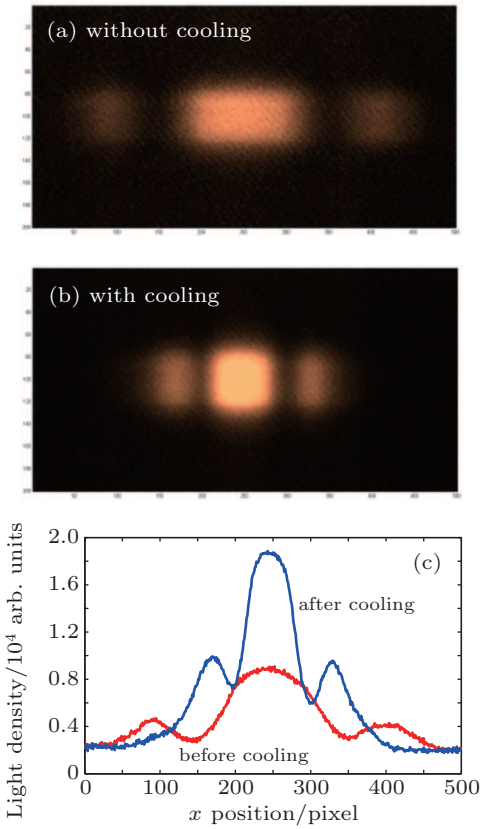


Fig. 2. (color online) The effect of laser cooling ((a) without cooling, (b) with cooling) and fluorescence density curve (c).

In order to optimize the transverse cooling of the Cr atom beam and compress the velocity distribution without atom flux loss, the rectangular cooling laser is 2 mm × 20 mm and the laser frequency detuning is −5 MHz with a power of 25 mW. Some typical cooling fluorescence images are shown in Fig. 2.

The knife-edge measuring method shows that the Cr atom beam has a transverse cooling temperature that is better than 418 μK.[17] After comparison with the fluorescence density curve, it is obvious that the atom flux has been enhanced and that it is now twice bigger than it was before. The Cr atoms are deposited onto the InP substrate after the laser cooling, and inherent parallel gratings are formed. In the experiment, the focusing laser's power ranges from 15 mW to 40 mW, with a waist radius of about 200 μm, and the frequency detuning is 250 MHz.

3. Measurement setup

In order to characterize the structural distribution of deposited Cr gratings, a calibrated commercial AFM is used to measure them with high accuracy. We have used a commercial AFM, which is a Dimension Edge that is produced by the Bruker Corporation. This AFM is calibrated with the transfer standard (VGRP-15M), and its measured results can be processed offline with the nanoscope analysis software. In order to investigate its accuracy at the nanoscale, we measured a 2D200 grid standard of nanosensors. The measured results show that the grid standard of x axis is 200.0±0.1 nm. Compared with the results offered by Physikalisch–Technische Bundesanstalt (PTB), $d = 199.995 \pm 0.027$ nm, the commercial AFM also shows a high accuracy at the 200 nm scale, which is very similar to the Cr nano-grating's pitch standard (212.78 nm).

4. The distribution characteristics of the Cr grating

Based on the repetitive measurement, we have analyzed the measurement results and drawn a conclusion about the Cr nano-grating's characteristics, as follows.

(i) The pitch standard is highly parallel and uniform, which is traceable to the wavelength of the laser standing wave.

(ii) The peak-to-valley height (PTVH) is better than 25 nm, which satisfies the requirement of application.

(iii) The feature width broadening of the Cr structure is obvious along the standing wave direction; and the PTVH along the Gaussian direction appears to be in accordance with Gaussian distribution.

(iv) The deposited Cr nano-grating area shows high growth uniformity.

In the following, the specific analysis of the above characteristics is given.

4.1. Highly parallel and uniform

Figure 3 offers two-dimensional AFM images given by the calibrated commercial AFM. Both of the images are located at the same sample, but with different offset distances along the standing wave direction. In Fig. 3(a), the PTVH of the Cr nano-grating is only 0.2 nm. The scanned image basically demonstrates the scaly structure of the InP substrate, and the Cr nano-gratings are indistinctly to be seen. In Fig. 3(b), the PTVH is 20 nm, the Cr structure is highly parallel and no contaminations are found in the scanned area, which indicates clean depositions.

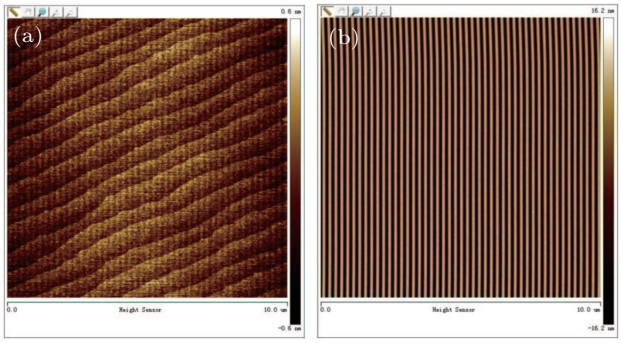


Fig. 3. (color online) Two-dimensional AFM images given by the calibrated commercial AFM. (a) PTVH = 0.2 nm, (b) PTVH = 20 nm.

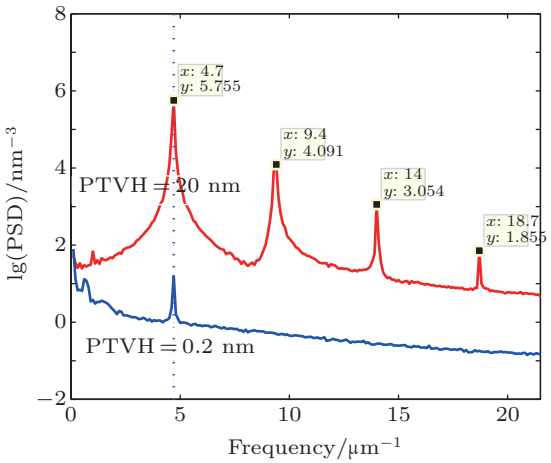


Fig. 4. (color online) The power spectrum density comparison of Cr nano-grating.

The power spectrum density (PSD) analysis results of Cr nano-grating with different PTVHs are shown in Fig. 4. Although the PTVH is only 0.2 nm, its PSD has an obvious peak at $f = 4.7$ μm^{-1}, and the corresponding pitch d is

$$d = 1/f = 1/4.7\ \mu\text{m} \approx 212.8\ \text{nm},$$

which agrees well with half of the standing wavelength ($\lambda/2 =$ 212.78 nm). When PTVH increases to 20 nm, its PSD distribution also peaks at $f = 4.7$ μm^{-1}. Because the PSD method essentially belongs to the Fourier transform method, frequency multiplication signals appear simultaneously and attenuate gradually, for example: $f = 9.4$ μm^{-1}, $f = 14.0$ μm^{-1}, $f = 18.7$ μm^{-1}, and so on. The NIST researchers have analyzed the accuracy of the Cr pitch standard, and their results have indicated that the Cr pitch has a relative uncertainty better than 2.5×10^{-5}.[18]

4.2. PTVH is better than 20 nm

Figure 5(a) is the three-dimensional (3D) image of Cr nanostructures scanned by the commercial AFM, and Figure 5(b) is the section line of Cr nanostructures spanning 4 μm. Figure 5(b) shows that the Cr nano-grating structures are distinct with little fluctuations at its peaks' height, and its PTVH is up to 25 nm. Currently, the international pitch standard exceeding 10 nm's PTVH can satisfy the practical applications. Because the Cr grating's full width at half maximum is 60 nm to 120 nm, further investigations need to be conducted to minimize the feature width.

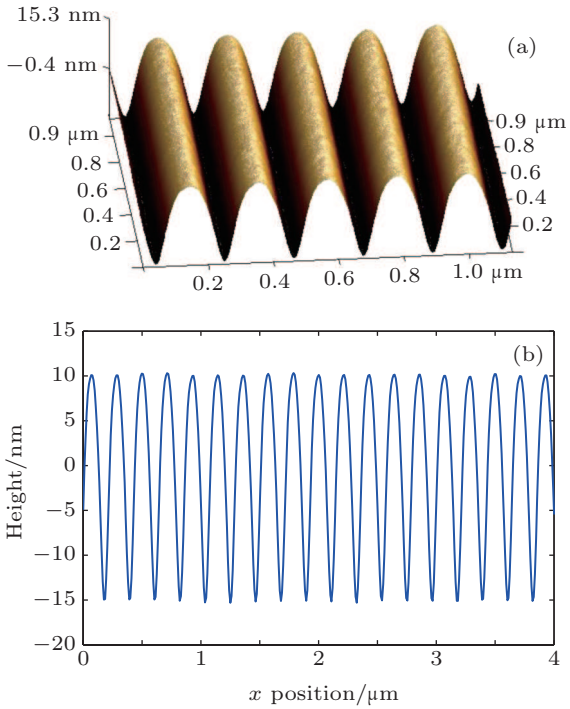


Fig. 5. (color online) (a) 3D image of Cr nanostructures (area: 1.1 μm×1.1 μm), (b) the section line of Cr nanostructures (length: 4 μm).

4.3. Feature width broadening

The mapping measurement result of Cr-deposited structures is an applicative method to investigate the PTVH distribution characteristics. Figure 6 shows the 3D image of PTVH distribution of one sample (No. 130419). The temperature was 23°, the humidity was 48%, the cooling laser power was 35 mW, and the focusing laser power was 28 mW with a waist radius about 200 μm. The focusing laser was cut by the substrate with a 10% laser power loss. Figure 6 indicates that the Cr nano-gratings covers an area of 1000 μm×300 μm with a best PTVH of 21.5 nm in this time's measurement. It must be specified that the repeated measurement may cause a

discrepancy.[1] The Cr area where PTVH exceeds 10 nm covers about 600 μm×200 μm, which accounts for about 40% of the whole area. If a wider slit is used for mechanical collimation, the transverse structure's width can easily exceed 2000 μm, which reaches the scale of millimeters. The feature width broadening and height increasing of the Cr nanostructure have been experimentally observed in the gradual atom flux distribution divergent area on one sample along the standing wave direction.[19] Meanwhile, the Gaussian distribution of the laser standing wave makes its corresponding PTVH conform with a Gaussian distribution. In the experiment, the relative position of the standing wave and the substrate is a key issue for atom deposition. A polarized beam splitter is inserted into the optical system to accurately identify the relative position,[20] and the tilt between the substrate surface and the Gaussian direction, which mainly lead to the dissymmetry distribution of PTVH that is shown in Fig. 6.

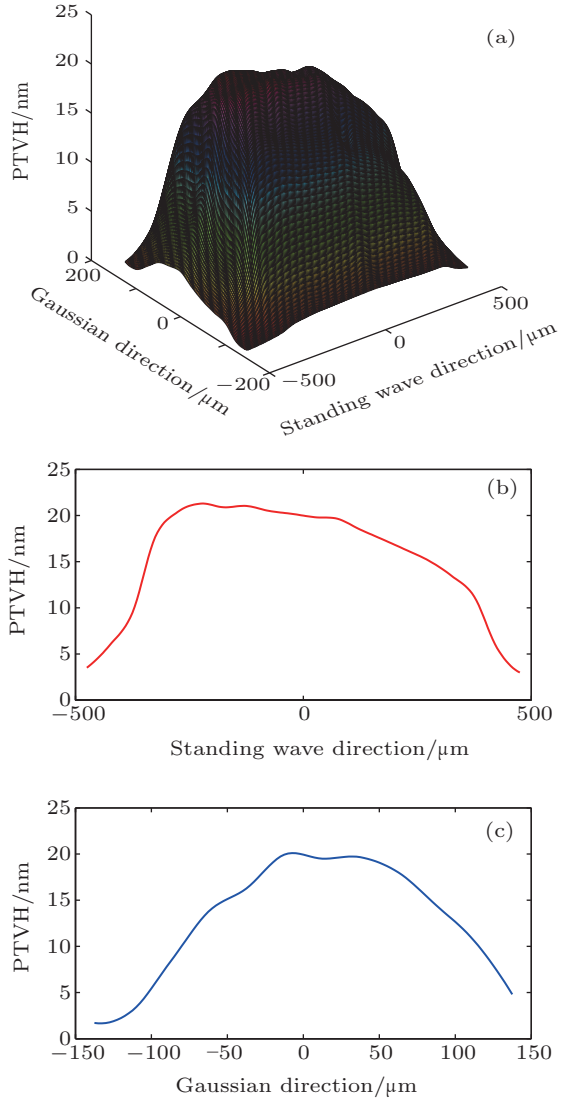


Fig. 6. (color online) 3D image of PTVH distribution (a) and distributions along the standing wave direction (b) and the Gaussian direction (c).

4.4. High growth uniformity

The substrate for Cr deposition is prevailingly silicon, but Qian *et al.*[20] have successfully introduced an InP substrate for deposition, which means that the Cr deposition area can be seen with naked eye observation (Fig. 7(a)). In Fig. 7(b), the 3D image with an area of 10 μm×10 μm indicates that the scaly structure of the InP substrate has been maintained after 3 h of deposition. This is the direct evidence of the Cr deposition's high growth uniformity.

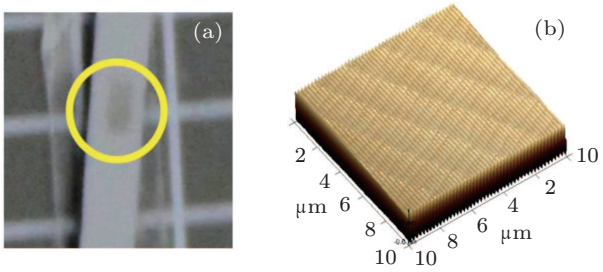


Fig. 7. (color online) (a) Cr deposition area with naked eye observation; (b) 3D AFM image.

5. Key issues

In order to improve the applications of Cr atom lithography, some key issues should be considered, as follows:

1) The Cr atoms' deposition rate. Compared with the relative science reports, our results of the deposition rate are only 10–15 nm/h at a distance of 70 cm to the Cr oven, which is relatively low.

2) Positioning of standing wave against the substrate. Generally, the cut proportion of focusing laser power is less than 10%. The position between standing wave and substrate plays an important role in the depositional structures' quality.

3) The find-me structure method. Although the deposited area can be seen with the naked eye, it is still not convenient to find the specific structures in the Gaussian direction.

4) The stability of the laser light system. In order to construct a stable laser, the light system is essential for the efficiency of repetitive experiments. In addition, the polarization of cooling and focusing laser should be considered.

6. Conclusions

We introduced the basic theory and experimental results of Cr atom lithography, studied the Cr nano-grating's distribution characteristics, and analyzed the key issues that had previously remained unsolved. Direct traceability, a highly parallel and uniform pitch standard, a big area at the millimeter scale, and high growth uniformity have indicated the great potential of Cr nanostructures to be used as a length calibration standard.

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