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Laser-focused Cr atomic deposition pitch standard as a reference standard

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ABSTRACT

A chromium (Cr) grating pitch standard is fabricated by a technique of laser-focused atomic deposition. Cosine errors of the grating standard are analyzed and controlled under a relative error of 6×10^{-6} after 10-times iterative calibration. The dimension properties of the standard are measured and analyzed by a calibrated metrological atom force microscope (AFM) with large range. The experimental results show the grating standard has a good uniformity and structural periodicity. Hence, the laser-focused Cr atomic deposition grating can work as a reference standard.

1. Introduction

Recently, many micro- and nanoscale measurement instruments have been introduced for the precise measurements, such as scanning probe microscopes (SPM), scanning electron microscope (SEM) and optical interference microscopes. Analysis about the measurement instruments and establishment of the quality assurance systems are quite important since quantitative measurements presuppose reliable and stable instruments, suitable measurement procedures as well as calibration artifacts and methods [1,2]. In a conventional nano dimension system, the laser interferometer is introduced as the units for most of the applications to take available analysis. However, due to the price, application environment and measurement speed, the metrology structure of laser interferometer is limited in the metrology measurement instruments [3]. To calibrate these measurement instruments and trace the measurement data back to the SI length standard [4], an accurate and traceable metrology transfer standard is developed in nano- and micro-technologies.

In this paper, a laser-focused atomic deposition is introduced to fabricate a pitch standard as a reference standard. A $\lambda/2$ (212.7 nm) pitch of laser-focused Cr atomic deposition grating is fabricated. A metrological AFM with a large range is set up as a positioning and measuring instrument. To evaluate the atomic deposition grating as a new pitch standard, an effective guide method is used to analyze the measurements of Cr deposition grating. The correction of the orthogonal scan direction is calibrated to eliminate cosine error of the measurement results. Finally, the feasibilities of Cr atomic deposition grating are measured and discussed.

2. Laser-focused Cr atomic deposition grating

Laser-focused atomic deposition is a new technique for nano fabrication [5], in which, atoms are deposited onto a substrate through a near-resonant laser standing wave and formed into parallel lines onto a substrate. The pitch fabricated by this technique is directly traceable to the standing laser wavelength, which improve practical application with less error brought by the dimension

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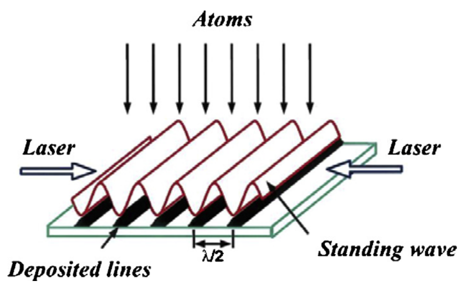

Fig. 1. Schematic of laser-focused atomic deposition based on standing laser wave.

transfer process. And, the structure has a good periodicity, uniformity, spatially coherent consistency and stability with clear fringes and high resolution [6]. Using Na [7], Cr [8,9], Al [10], Yb [11] and Fe [12] atoms depositing onto a substrate through a laser standing wave grazing across the surface has been successfully demonstrated. Also, λ/4 (106.4 nm) [13], λ/8 (53.2 nm) [14] pitch standards and hexagonal nanostructures [9] have been generated for micro-metrology and nano metrology pitch standards. Hence, laser-focused atomic deposition technique is taken to fabricate an accurate and pitch standard in the manuscript.

A grating standard sample is fabricated using laser-focused atomic deposition as shown in Fig. 1 [15]. The principle is based on the radiation pressure of a standing laser wave field with the particular spatial distribution to control atomic motion and create nanostructures [16]. The laser light is nominally single-frequency (line width of 1 MHz or less) and stabilized at a frequency near a strong optical absorption line of the atom transition. With suitable choice of laser intensity (usually a few watts per square millimeter) and detuning from the atomic line center (usually a few hundred megahertz), the nodes of the standing wave will act as an array of "lenses" for the atoms, concentrating them into an array of lines on the substrate [17].

In this experiment, Cr is chosen as an ideal element for laser-focused atom deposition, which has a low surface diffusion and high chemical stability, this make it suitable for an etch mask. The wavelength of laser standing wave is selected to match the $^7S_3 \rightarrow {}^7P_4{}^0$ transition of Cr (λ = 425.55 nm). Because the atomic transition frequency is very stable and the relevant cooling laser-focused frequency is very precise, the pitch of Cr deposition grating can be directly traced back to half of the laser wavelength.

Fig. 2 shows the experimental setup of laser-focused atomic deposition, which is composed of vacuum system, Cr atomic furnace, laser light sources and frequency stabilization device and the optical system. This laser is divided into four beams: the first is for laser frequency stability using a laser-induced fluorescence (LIF) technique; the second and third from the zero order diffraction of an acoustic-optical modulator (AOM) are individually for the laser cooling beam and the fluorescence detecting beam; and the fourth is +1 order diffraction of the AOM (frequency shifted +200 MHz) for laser focusing used to deposit a period nanostructure. A standing light field is obtained such that the fourth beam with a 100 μm waist is retro-reflected by a 0° mirror (reflection larger than 95%), which is directly against one face of the right-angle prime and perpendicular to the substrate [18]. All depositions were carried out in a turbo-molecular pumped vacuum system with typical pressure10^{-5} Pa. When the molecular beam epitaxy oven is at 1650 °C, the Cr atomic beam is produced by thermal evaporation out of an orifice.

According to thermodynamics theory, on the direction of movement, the movement of the Cr atomic beam should comply with Maxwell–Boltzmann distribution as:

$$\rho_o(v_z) = \frac{1}{2}\left(\frac{M_a}{k_B T_0}\right)^2 v_z^3 \exp\left(-\frac{M_a v_z^2}{2k_B T_0}\right) \quad (1)$$

where k_B is the Boltzmann constant, M_a is the mass of Cr atom, T_0 is the temperature of the atom beam. A 1650 °C high-temperature oven produces a Cr atom beam with the most-probable mean longitudinal (z direction) velocity of 960 m/s. Meanwhile, the transverse velocity distribution is given by the Gaussian distribution:

$$\rho_c(v_x) = \sqrt{\frac{M_a}{2\pi k_B T_c}} \exp\left(-\frac{M_a v_x^2}{2k_B T_c}\right) \quad (2)$$

Then, under the collimation based on the Doppler cooling technology, Cr atoms are deposited onto the InP substrate, forming

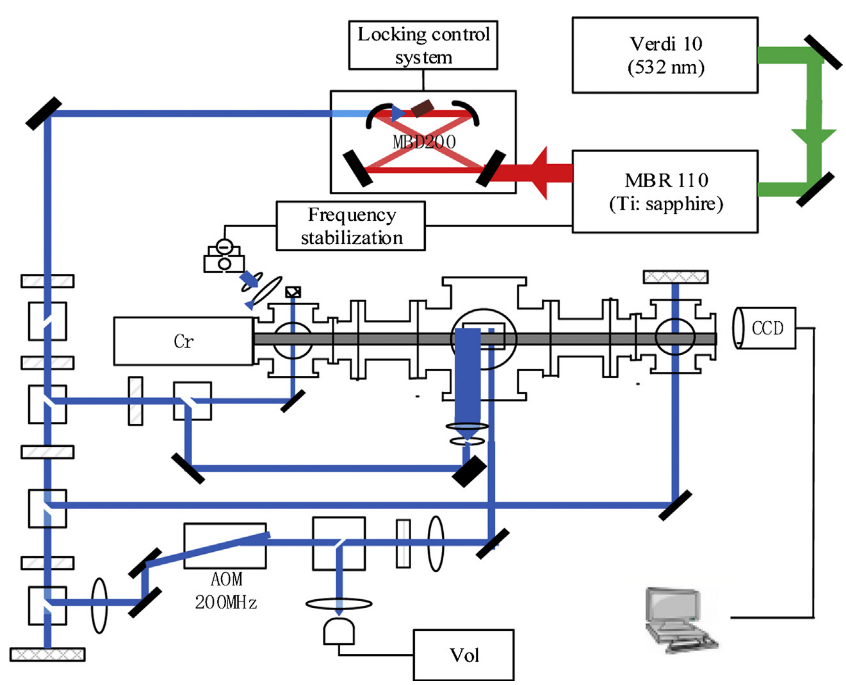

Fig. 2. The experimental setup of laser focused atom deposition, CCD: charge coupled device, AOM: acoustic-optical modulator.