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Nanoscale displacement measurement by a digital nano-moiré method with wavelet transformation

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The moiré method is a well-developed in-plane deformation measurement technique with the advantage of being full-field and non-contacting. It has been successfully applied in micro-scale measurements. The digital nano-moiré method is derived from AFM and STM (AFM/STM) moiré methods. Fig. 1 schematically illustrates the method, where the periodic lines with a period pitch of p_s represents image of the specimen grating and the lines with a period pitch of p_r represents the reference grating lines generated by the AFM/STM system monitor. Moiré patterns are formed by the interference between the scanned-in image of the specimen grating and the monitor-generated scanning lines. In this paper, the digital image generating process allows the pitch and the orientation of the virtual reference grating to be adjusted freely. The freely adjustable orientation allows the deformation fields to be measured in every desired direction by simply rotating the virtual reference grating. Meanwhile, the phase- shifting technique also benefits from the virtual reference grating's instantaneous phase adjusting capability. Fig. 2 shows the schematic diagram of the parameters and coordinates that characterize a virtual reference grating image, of which the size can be instantaneously adjusted to accommodate the image of the specimen grating. In addition to the size, there are three parameters to be set for a virtual reference grating image. Those three parameters are instantaneously adjustable, too. One of the parameters sets the pitch of the virtual reference grating p_r. The pitch of the virtual reference grating has to be set to equal the pitch of the specimen grating p_s, *i.e.*, $p_r = p_s$. Otherwise, the mismatch problem takes place. The second parameter is the direction angle θ. It should be tuned to make the reference grating lines parallel to the specimen grating lines. The last parameter is the relative displacement offset of the virtual reference grating δ. It is noted that he phase-shifting technology requires changing the relative displacement offset δ of the virtual reference grating. By setting the relative displacement offsets of the virtual reference grating to be $p_r/4$, $p_r/2$, and $3p_r/4$, we obtain the moiré patterns with the corresponding phase shifts of $\pi/2$, π, and $3\pi/2$, respectively. The overlapped moiré image contains not only the target moiré patterns but also the unwanted grating lines and noises. The unwanted grating lines and noises will distort the phase-shifting results. The wavelet transformation (WT) has been known for the abilities of characteristic detection and noise elimination. Thus, the proposed method employs WT to capture the target moiré patterns embedded in the noisy overlapped image.

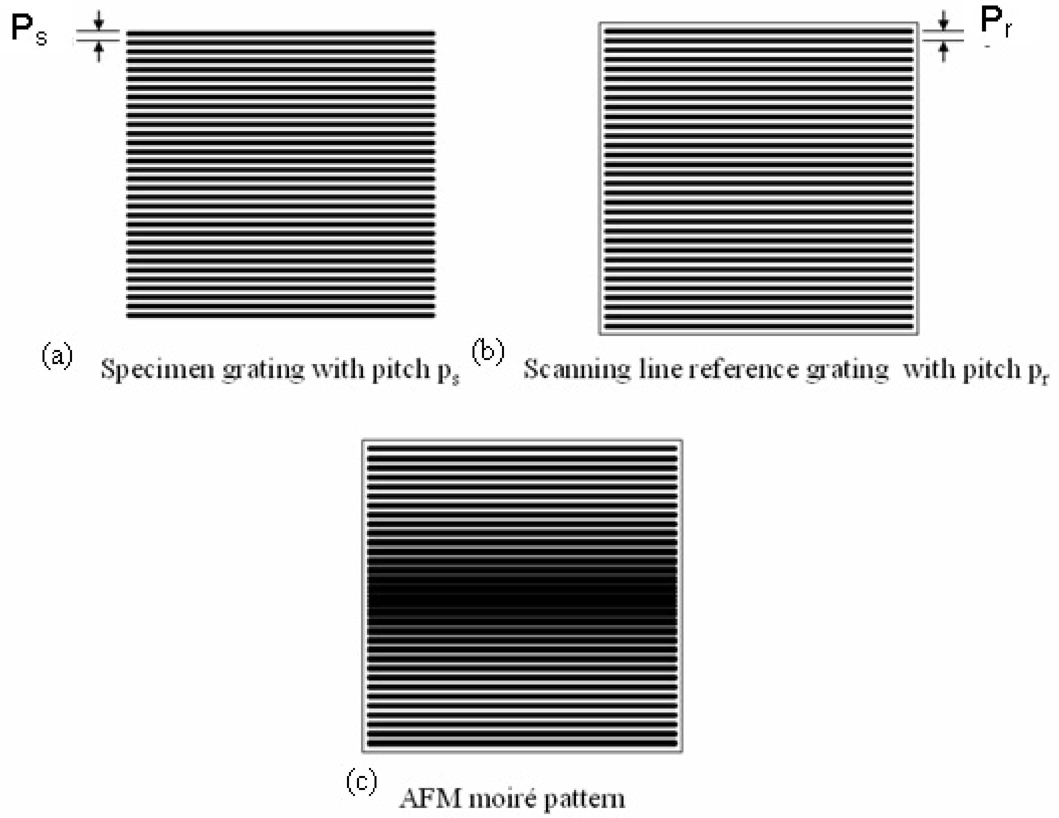

Fig. 1. Schematic diagrams of AFM and STM moiré methods.

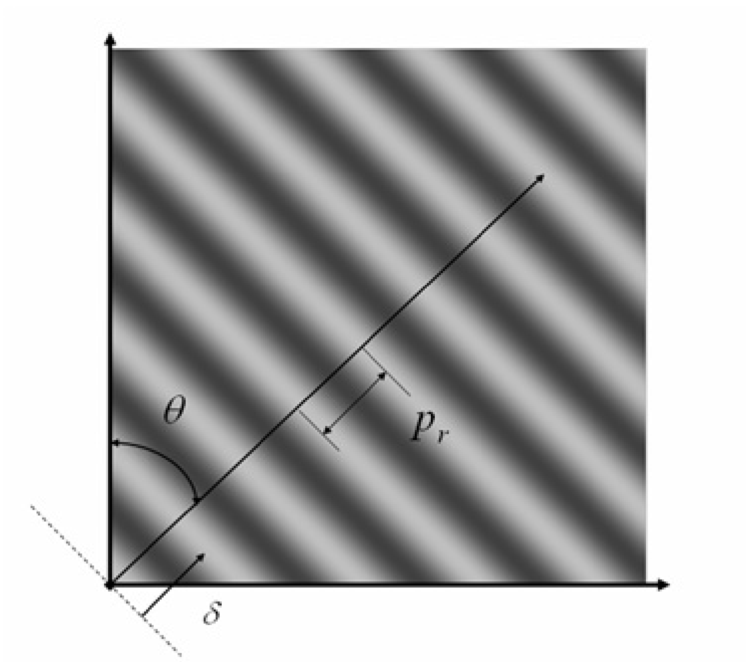

Fig. 2. A virtual reference grating image.

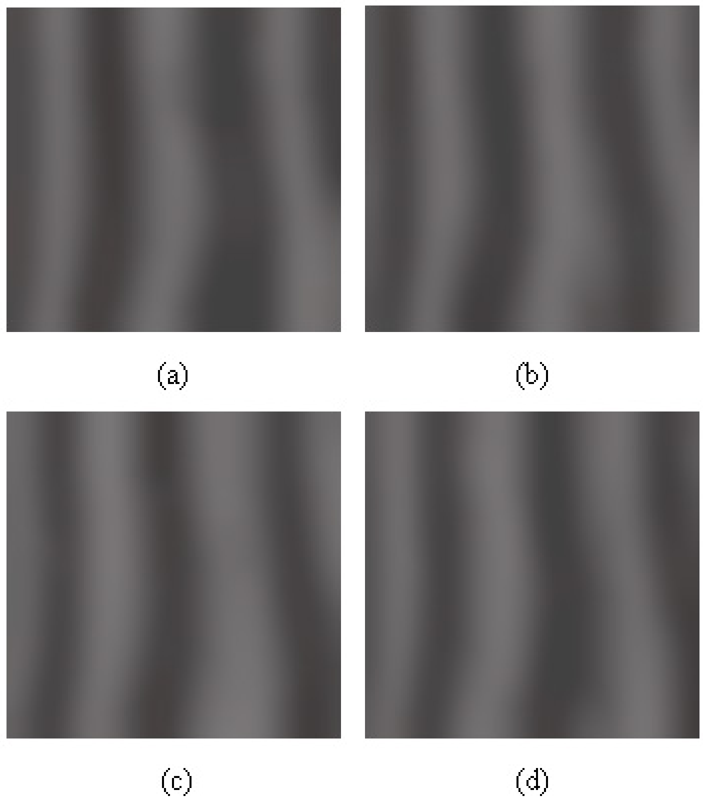

Fig. 3. The resultant moiré pattern images with different phase in the x direction ($30\mu m \times 30\mu m$).
(a) δ =0. (b) $\delta = \pi/2$. (c) $\delta = \pi$. (d) $\delta = 3\pi/2$.

To demonstrate the feasibility of the proposed digital nano-moiré method with WT, we measure the thermal surface residual deformation of a silicon specimen. A PMMA nanostructure array layer was used as the specimen grating to generate the moiré pattern. The periodic nanostructure array specimen grating was fabricated by e-beam lithography, and the equally spaced array orthogonally sticks out of a circular cross section plane. The manufacturing process is expressed as follow. First, the PMMA resists were spin-coated on the silicon wafer (the thickness of the PMMA resists were about 100nm) before baking (the baking temperature is 160℃). Then, the PMMA nanostructure array layer was processed by e-beam exposure and development. Finally, the PMMA nanostructure array layer was baked at 30℃. The specimen surface was irradiated by a pulsed KrF laser to produce the desired thermal surface residual deformation. The laser fluence was 0.8 J/cm^2, and the irradiated area was 1mm×1mm. One shot pulsed laser was irradiated on the silicon surface to generate the thermal surface residual deformation. A $30\mu m \times 30\mu m$ area of the deformed silicon wafer was scanned by AFM. The distance between the center of the irradiated area and the AFM scanning area was 1.5mm. The image of deformed silicon wafer was overlapped with the virtual reference grating to generate the moiré pattern. Then, we used the WT to extract the target moiré patterns. The phase-shifting technology was carried out by changing the relative displacement offset of the virtual reference grating. The four-step phase-shifting moiré fringe patterns in the x direction are given in Figs. 3(a-d). The continuous wrapped displacement field in the x direction can be obtained in Fig. 4(a). To obtain the continuous displacement field in the y direction, we rotate the direction angle θ by 90^0, and the continuous wrapped field displacement in the y direction can be obtained in Fig. 4(b) in a similar manner.

Fig. 5 shows the unwrapped phase maps and fringe distributions from Fig. 4. From the continuous displacement fields, it can be seen that the displacement fields are uniform generally. However, it is observed that the displacement fields are slightly wavy; it may be caused from the non-uniform thermal residual deformation induced from the insufficient smoothness of the wafer surface. The total strain components were caused from the thermal residual strain and the initial strain from the mismatch problem. However, if the virtual reference grating was calibrated to match the specimen grating, the initial strain can be ignored. The distribution of the thermal residual strain components according to the illumination center of KrF laser in the x direction is shown in Fig. 6.

The digital nano-moirés method with WT has been explored to measure the nanoscale in-plane displacement field. The moiré patterns are generated by overlapping the images of the PMMA nanostructure specimen grating and the virtual reference grating. For demonstration purposes, the proposed method has been carried out, and we achieved nanoscale measurement with 170 nm resolution. Experimental results reveal that the proposed method is feasible and can be carried out for the nanoscale displacement measurement. The proposed method employs the virtual reference grating to replace the traditional scanning lines reference grating. The pitch and the direction of the virtual reference grating can be instantaneously adjusted to avoid the mismatch problem. Additionally, the adoption of a virtual reference grating allows displacement fields of the other direction to be obtained by simply resetting the direction angle. Besides, the four-step phase-shifting technology can also be executed by simply resetting the displacement offset of the virtual reference grating. The specimen and experimental setup are kept stationary during the measuring process, thus mechanical errors are trivial.

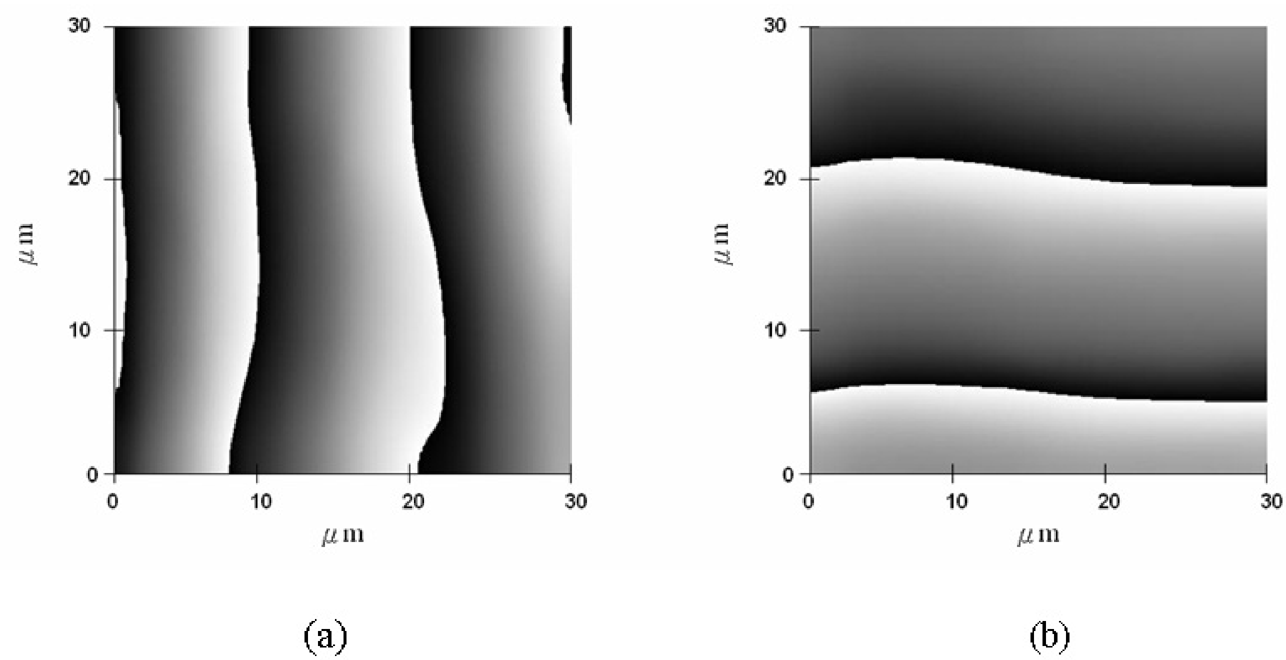

Fig. 4. Wrapped phase-shifting images ($30\mu m \times 30\mu m$). (a) x direction. (b) y direction.

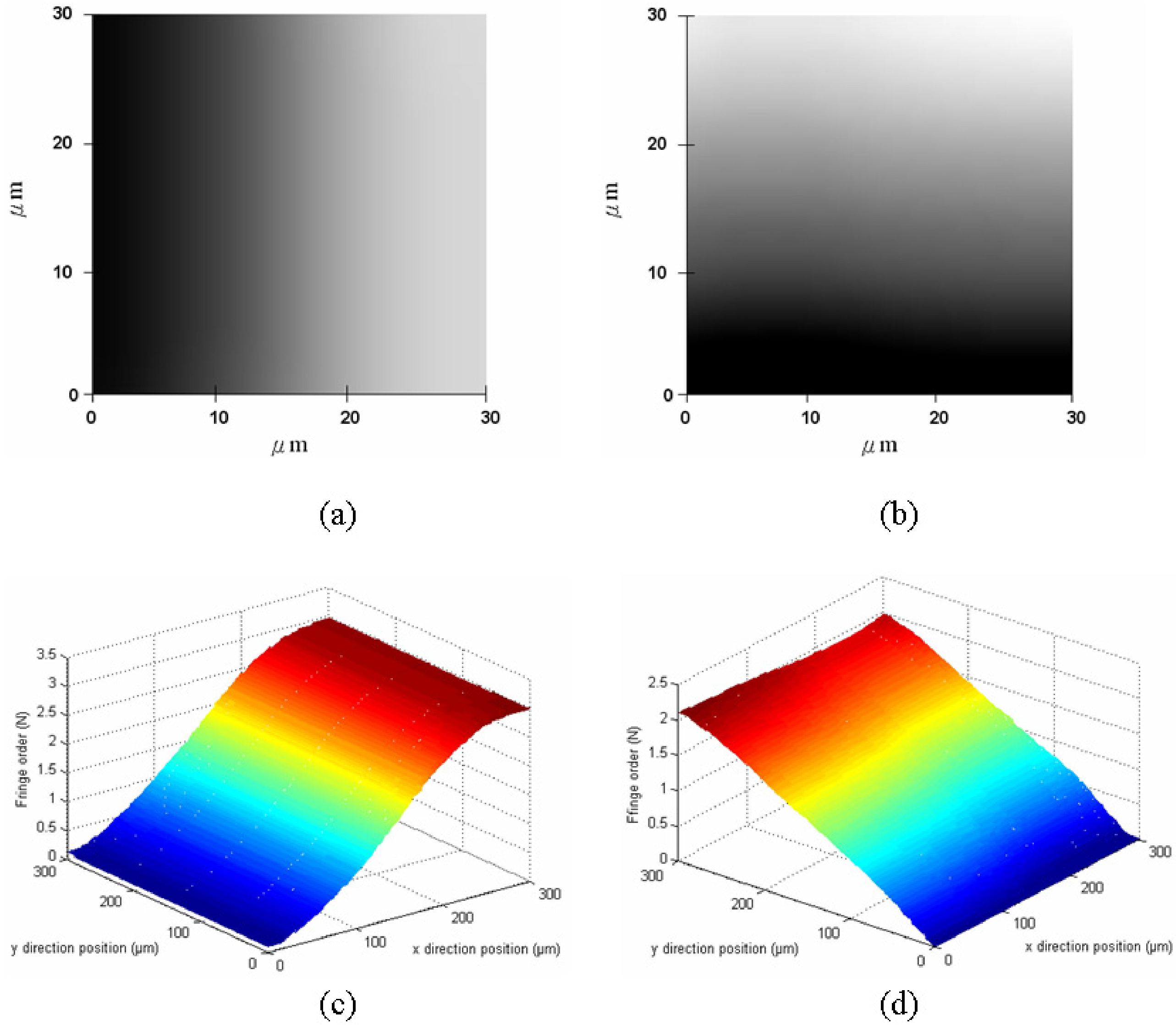

Fig. 5. Unwrapped phase map from Fig.4. (a) x direction. (b) y direction. (c) the moiré fringe order distribution in the x direction. (d) the moiré fringe order distribution in the y direction.

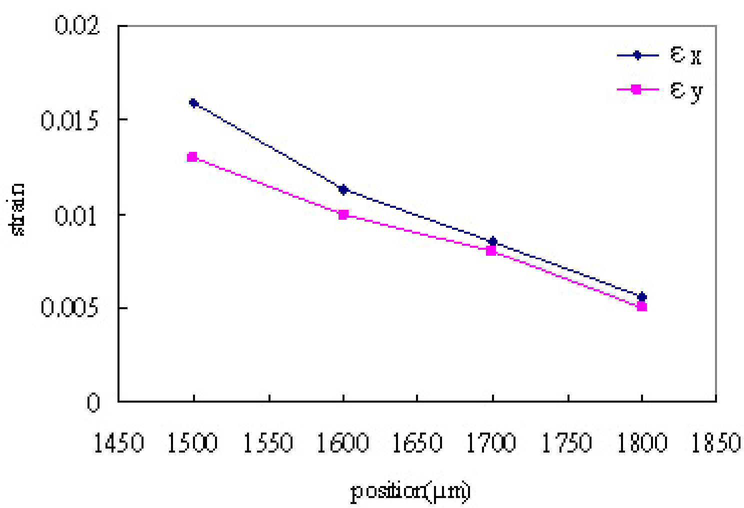

Fig. 6. The distribution of the thermal residual strain components according to the illumination center of KrF laser in the x direction.

On the other hand, the proposed method, employing WT to nullify the unwanted grating lines and noises, is capable of accurately capturing the target moiré patterns. Thus, the accuracy of the phase-shifting result is enhanced, and consequently the accuracy of the digital nano-moiré method is greatly improved.