Supporting Online Material

"Sub-Diffraction-Limited Optical Imaging with a Silver Superlens",

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In this section, we present experimental procedures including the fabrication steps of the sample in detail.

Sample fabrication in overview

Our sample configuration is shown in Fig S1. A Cr layer is deposited on a quartz wafer and mask patterns are fabricated into the Cr film. The surface of the mask is planarized with a PMMA spacer layer, and then the silver film, which acts as the superlens, is deposited on top of the spacer layer. Finally, photoresist is deposited directly onto the silver superlens to record the nearfield image through photolithography.

Mask fabrication

Starting with a quartz wafer, 50nm Cr layer is deposited through electron beam evaporation. The objects then are patterned into and through the Cr layer using Focused Ion Beam (FIB) milling. A Strata 201XP FIB by FEI Company was used to fabricate grating objects with a 60nm line width. Fig. S2A shows a picture of 120nm pitch grating objects measured by Atomic Force Microscopy (AFM) after the fabrication. The line roughness due to the imperfectness of FIB process will affect the edge definition of the final images after the photolithography.

Planarization

In order to prepare a flat superlens on top of the objects, a spacing layer to eliminate the surface modulations of the Cr objects is required. This layer must also be thin to prevent significant decay of the evanescent waves created by the objects. This task is done by adding a 40nm Poly(methyl metacrylate) (PMMA) layer onto the Cr object layer.

The PMMA used in this step is 495K molecular weight A4 PMMA from Microchem Inc. First, we gradually reduce the surface modulation through multiple spin-coatings of PMMA layers, which is a semi-conformal process. This step creates a thick(~1μm) planarized PMMA layer. Our desired thickness is achieved by O_2 plasma etching. The sample is placed in a Tegal plasma asher where the PMMA layer is blanket-etched. After a short etching(1-2min), the thickness is measured with a Filmtek 2000 film thickness monitor. The etching and measurement steps are repeated until the desired thickness is reached. Finally, the etched 40nm PMMA layer is reflowed above its glass transition temperature in order to smooth the surface roughness caused by the plasma etching.

Fig. S2B and Fig. S2C show AFM topography scans of a planarized 120nm pitch grating object. The topography is measured on a Veeco Dimension 3100 AFM system with sharp tips(Supersharp silicon tips from Nanosensors) with a 5nm radius of curvature. The height modulation of the grating is reduced close to 1nm after the planarization. The surface roughness (RMS) of the planarized PMMA layer is close to 0.5nm.

Superlens silver layer

On top of the PMMA spacer layer, 35nm of silver is deposited as our superlens material through E-beam evaporation. The smooth PMMA surface underneath improves the surface quality of the silver layer. It was also found that a faster deposition rate (>5nm/s) of silver resulted in better surface roughness control in comparison to slower rate of ~1Å/s., The rootmean square (RMS) surface roughness was measured on a 10micron by 10micron square area by AFM, and typical RMS roughness obtained on silver is less than 2nm. Fig. S2D and Fig. S2E show the AFM scans of the silver surface on top of the PMMA surface shown in Fig. S2B and Fig. S2C respectively. Fig. S2E clearly shows that the object grating modulation is completely removed after the silver deposition.

Photolithography

Photolithography is used to record the image of the subwavelength object. An I-line negative photoresist (PR), NFR-105G by JSR Micro, was used. The PR was diluted with 3 part of solvent (70% Ethyl Lactate and 30% Ethyl 3-Ethoxypropionate) to achieve 120nm thickness with single-step spin-coating process. After a 1 minute soft bake at 100°C, the sample was exposed from the substrate side under a 8 mW/cm^2 UV lamp. The 365nm light source is provided by a SUSS MA6 contact aligner integrated with I-line filter with a 365.8nm central wavelength and a 4.5nm (FWHM) spectral linewidth (Spectrum data provided by SUSS technical support). In addition to the 120 nm pitch gratings we also performed photolithography tests on a series of grating objects with periodicity varying from 140 to 180 nm. The exposure results are presented in Fig. S3. The detailed exposure and developing conditions are listed in Table S1. Imaging 100nm pitch is theoretically possible with 35nm silver, but currently we are unable to test it due to the resolution limit of FIB in our mask fabrication process.

Cross-sectional Analysis:

Averaged cross-sectional profiles are taken in our measurement to reduce the influence of possible defects in the mask fabrication, planarization, and image development processes. Fig. S4 illustrates the process steps for cross-sectional analysis. For the grating patterns, 200 scan lines were averaged in the direction normal to the gratings. In order to ensure sufficient lateral resolution of the line profiles in arbitrary patterns, additional zoomed-in scans were taken for Fig. 4D. Gaussian line fitting was used on the averaged line profile (Fig. 4D) to estimate the full-width at half-maximum (FWHM).

Control Experiment

Control experiments were carried out where the silver superlens layer is replaced by a PMMA layer of the same thickness (35nm), for a total PMMA thickness of 75 nm. The same exact planarization process was used and the PR was directly spin-coated on the PMMA surface. Fig.S5A illustrates the planarized surface of PMMA of the control sample on the 120nm grating object. Fig.S5B shows the exposure result for the control sample, indicating that even though the attenuated propagating waves can pattern a block of 40nm thick PR, 120nm period could not be distinguished on the recorded image. We also repeated the above control experiments with 140nm pitch gratings and the results are in good agreement with Fig S5B.

In addition, control experiments on arbitrary patterns ("NANO" mask in Fig 4A) were reprocessed. The linewidth of the control experiments without silver lens varies from 310 nm to 370nm, again supporting our argument of severe exponential decay of subwavelength features even at distance of 75nm away.

Sample	Exposure time	Developing time
120nm~180nm grating objects Superlens imaging	60sec	15~20sec
120nm grating object Control experiment	30sec	15~20sec
NANO pattern Superlens imaging	60sec	15~20sec
NANO pattern Control experiment	60sec	>1min

Table S1. Experimental exposure time and developing time to define the near-field image by cross-linking the negative resist (NFR-105G). Developer: 2 part of PD523AD is diluted by 1 part of DI water.

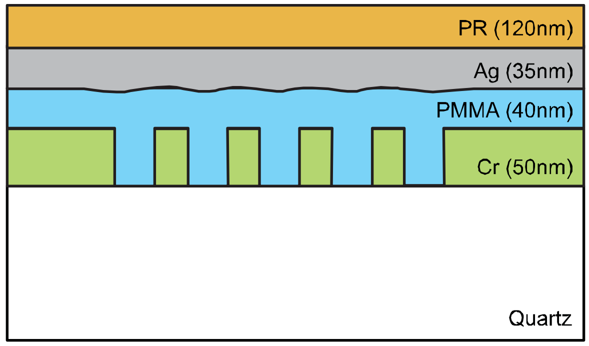

Fig. S1: Sample configuration for superlensing experiment. Cr (50nm) is evaporated on a quartz substrate, and the objects are fabricated using Focused Ion Beam milling. Then, the objects are planarized with a PMMA (40nm) spacer layer and the superlens silver film (35nm) is evaporated onto the PMMA. Finally, near field photolithography is performed to record the image of the sub-wavelength object. Notice the reduced modulation (<1.5nm) on PMMA surface.

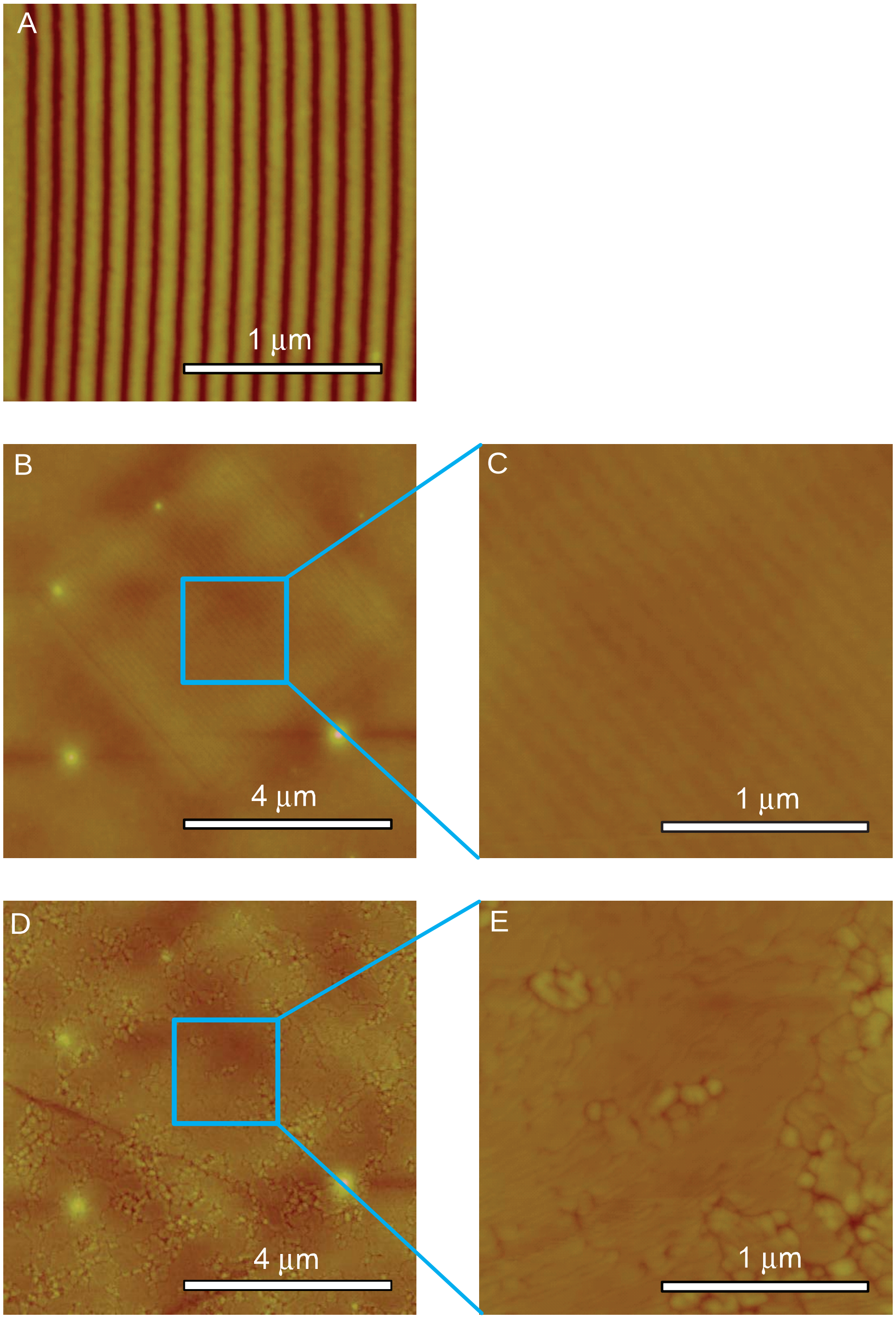

Fig. S2: A. AFM image of the 120nm grating object fabricated using Focused Ion Beam (FIB) lithography into the Cr layer(Fig. S1). B. AFM picture of the surface of planarized PMMA surface and the zoomed-in picture C of the boxed area. The height modulation of the grating object is significantly reduced(<1.5nm) by the PMMA layer. D. AFM picture silver superlens layer surface deposited on the PMMA layer, and its zoomed-in picture E. It shows that the modulation is completely removed after the silver deposition. All AFM images have 0-100nm height scale.

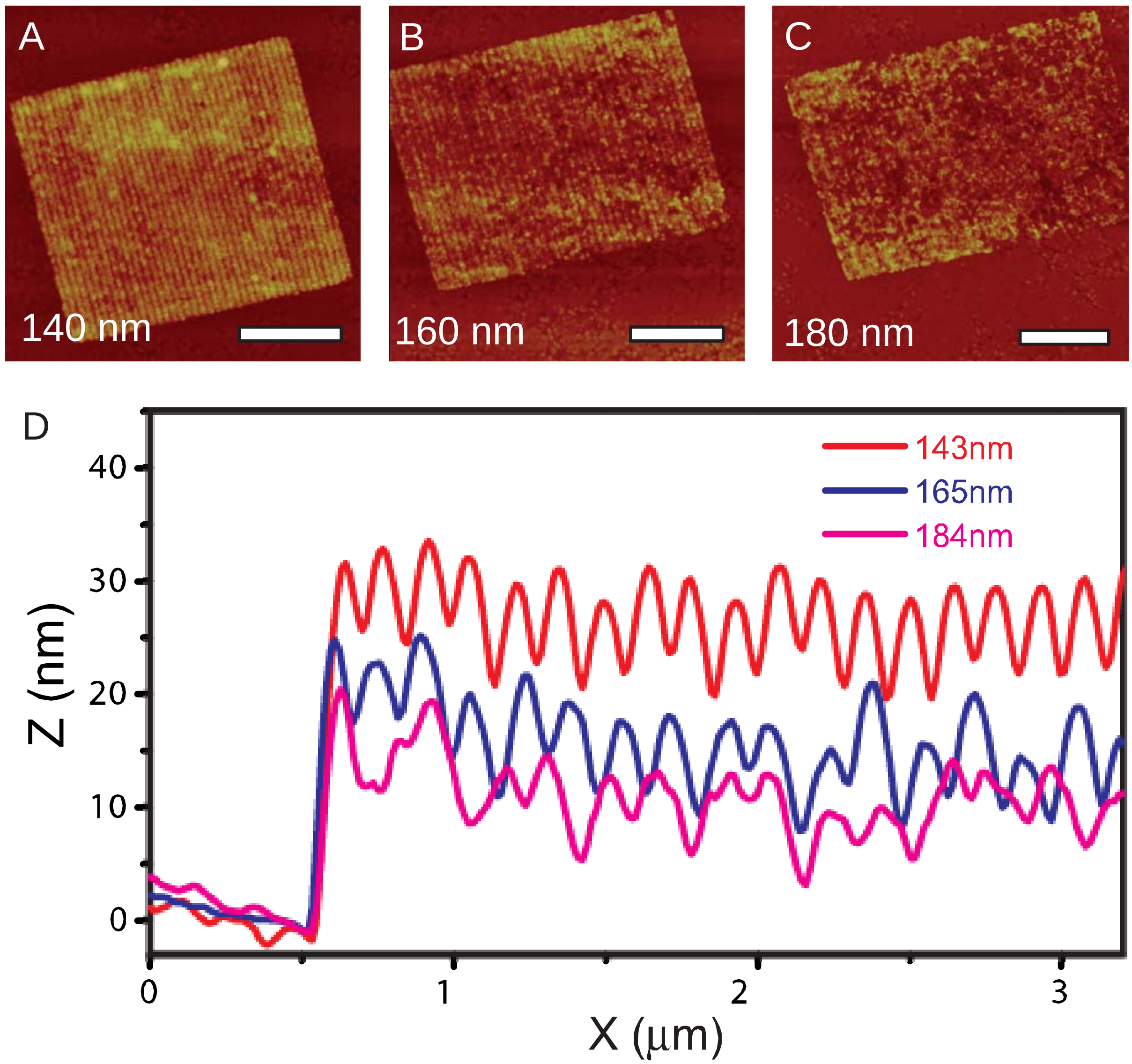

Fig. S3. Additional superlensing experiments on 140-180 nm (marked in white are designed value) pitch gratings. A. the AFM topography of recorded image in resists. The scale bar is 2micron for each panel. All AFM images have 0-100nm height scale.B. The averaged line cross-section profiles of recorded periodical grating images with actual pitch given by FFT analysis. This is an additional support for our finding of direct imaging with silver superlens.

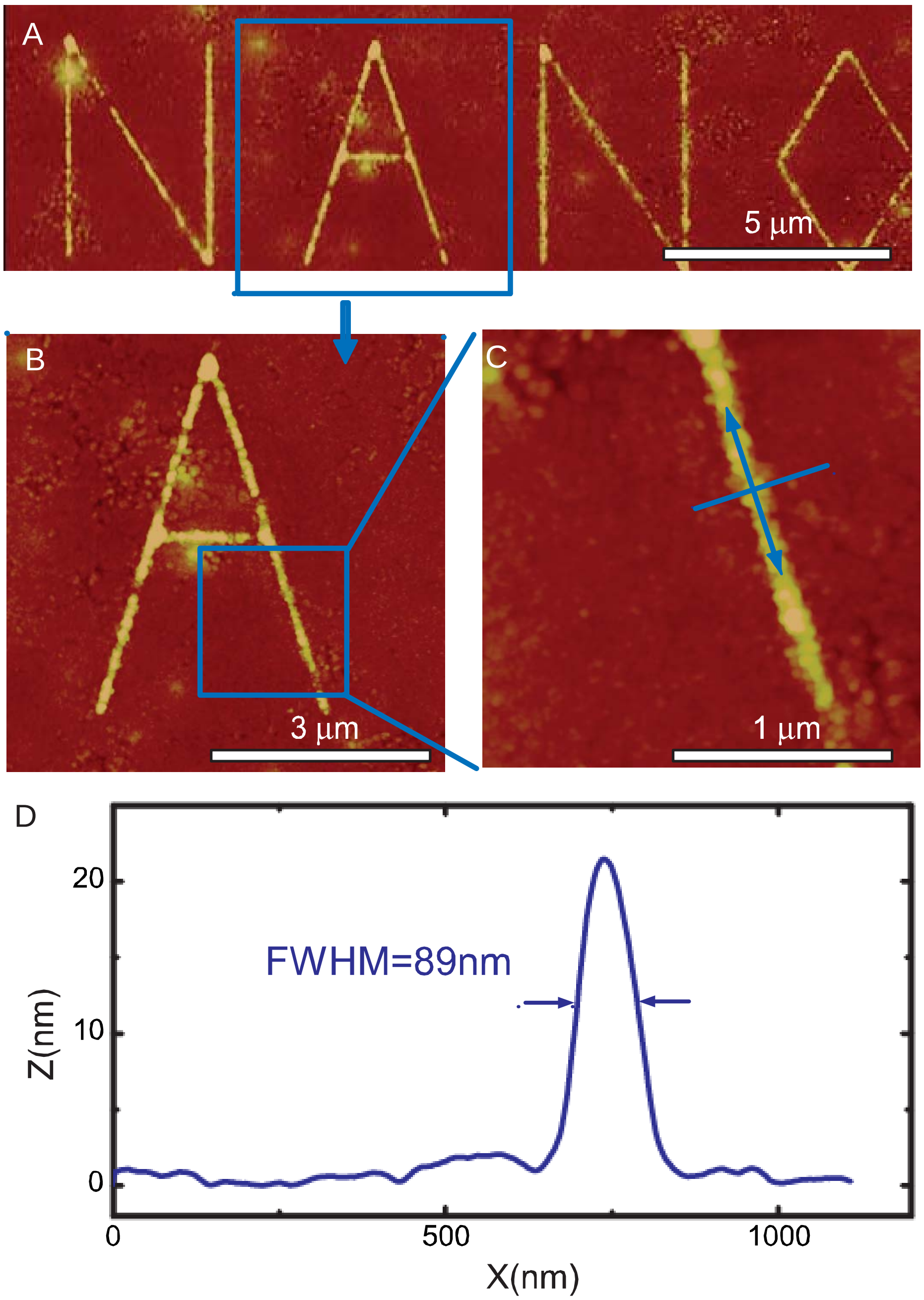

Fig. S4. Detailed procedures of obtaining averaged line cross-section profiles (Color Scale 0-50nm). A. AFM topography of NANO pattern of the recorded image(redrawn from Fig. 4B in text). B. Zoom-in AFM image of the letter “A”. C. A further zoomed-in scan for sufficient digitization of individual lines (in this case each pixel measures 3.9nm). D. Averaged height profile with a FWHM of 89nm.As many as 300 scan lines are measured and averaged in C in the direction normal to the double arrows.

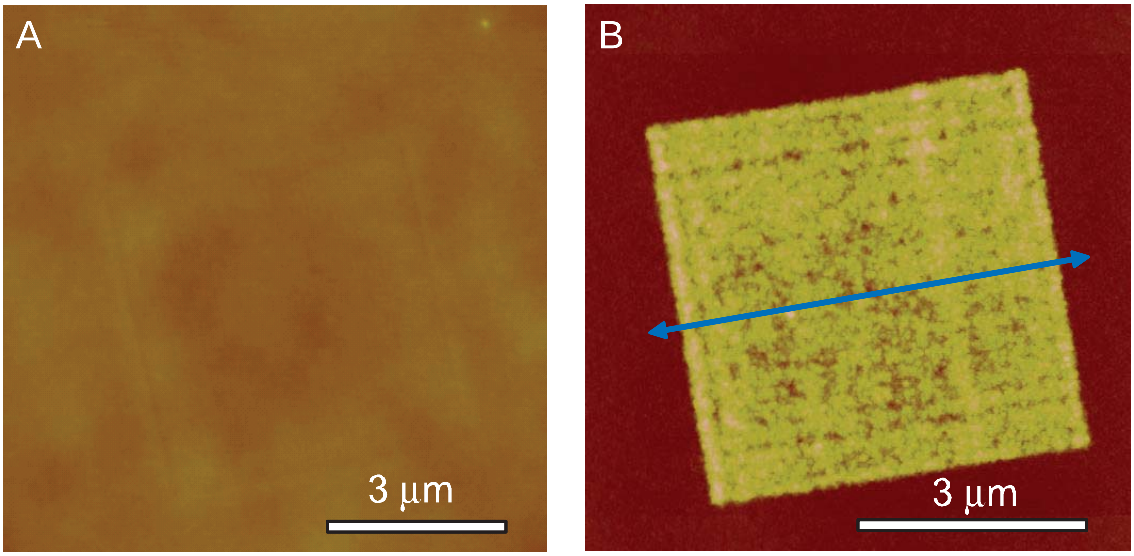

Fig. S5: A. Planarized surface of PMMA (75nm) of the control sample. The vague rectangular area in the middle (as shallow as 2-3nm) is the object with 120nm grating period. The color scale is 0-100nm. B. Control experiment photolithography result(color scale 0-100nm) and the average cross section direction (double arrow) of the recorded image (enlarged from Fig. 2C).