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២ Kwan Seob Park, Yoon Sung Bae, Sang-Soo Choi, et al.





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Kwan Seob Park,¹ D Yoon Sung Bae,¹ Sang-Soo Choi,² and Martin Y. Sohn^{1,a)}

AFFILIATIONS

¹ Physical Measurement Laboratory, National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA
² Photronics, Cheonan, Choongnam 31075, South Korea

^{a)}Author to whom correspondence should be addressed: martin.sohn@nist.gov

ABSTRACT

Pushing the resolution limit to the nanoscale is a critical challenge for applying the reflective Fourier ptychographic microscopy (FPM) to metrologies for characterization of nanoscale features. Characterization of opaque nanoscale samples using reflective FPM requires chiefly a light source with shorter wavelength to obtain nanoscale resolution, as state-of-the-art device sizes have become sub-100 nm or deep sub-wavelength. We report a reflective deep ultraviolet (DUV) FPM featured by an aperture scanning illumination based on the epi-illumination scheme for accommodating a 193 nm excimer laser source and a high numerical aperture (NA) catadioptric objective lens. The illumination system enables robust control of high-NA angular illumination and optimal energy fluence for FPM imaging and prevention of damage to the sample and optical components. The implemented reflective DUV FPM demonstrated image reconstruction of multiline targets with a minimum linewidth of 80 nm with an average contrast six times higher than conventional DUV microscopy.

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I. INTRODUCTION

Fourier ptychographic microscopy (FPM) is a novel computational imaging technique that allows for high space-bandwidth product (SBP) by synthesizing images generated with discrete angular illuminations that have high-frequency components beyond the cutoff frequency inherited by the objective used.¹⁻⁴ High SBP enables imaging without the need to compromise between high resolution and large field of view (FOV).⁵ This technique also has the capability for phase imaging, as it provides a complex field distribution from intensity measurements by a phase retrieval algorithm without using interference.⁶⁻¹³ Since Zheng et al. proposed FPM in transmission mode with these advantages,¹ various FPM modal platforms have been developed to enhance resolution,¹⁴⁻¹⁷ image quality,^{18,19} measurement speed,^{9,12,20} robustness,^{21,22} and to accommodate for applications not only with transmissive samples such as cells and biomedical structures,^{23,24} but also with reflective samples such as solid state materials and semiconductor devices.² Characterization of the reflective samples, such as state-of-the-art devices and artificial materials, requires development of reflection mode FPM with nanoscale resolution. $^{16.27-32}$

Resolution enhancement in FPM can be mainly achieved by systematic implementation to span the passband of the collection frequency contents far beyond the cutoff frequency and the use of a shorter wavelength light source. Despite the novelty of resolution enhancement techniques, such as high numerical aperture (NA) illumination using an oil immersion condenser or hemispherical illumination with visible light sources, they are hardly applicable for the reflection mode to measure reflective samples, such as in semiconductor device measurements, as the illumination and collection are positioned on the same side relative to the sample surface.^{16,33,34} A parabolic mirror mounted around the objective lens (OL) was proposed to make high NA illumination for resolution improvement in reflection mode FPM, resulting in a resolution of 244 nm, using a 515 nm light emitting diode (LED) source.³¹ The method is limited for measurement with respect to devices on large wafers.

Fourier ptychography (FP) has been accommodated to extreme ultraviolet $(EUV)^{30,55}$ and x-ray sources^{26,36} to achieve sub-100 nm

resolution with wavelength scaling. An FPM using an EUV light source of 13.5 nm was developed using an EUV mirror scanning method in reflection mode, reporting that the critical dimensions on a phase mask with a half-pitch of 112 nm were reconstructed for defect inspection.³⁰ A transmission mode FPM using an x ray of 0.14 nm wavelength was proposed, which achieved a 47 nm resolution limit through objective lens scanning.²⁶ The use of shorter wavelengths is certainly effective for enhancing the resolution of FPM to the nanoscale range. Though EUV and x-ray FPM systems significantly enhance the resolution down to sub-100 nm, they are limited for efficient implementation of FP optics in reflection mode for high angle illumination on the samples, because the freedom of optics design is limited compared to that of visible optics due to lacking infrastructure in refractive optical elements, such as lenses and mirrors, at those wavelengths. Using a deep ultraviolet (DUV) light source, which is highly compatible with efficient refractive and reflective optical components, enables efficient implementation of optics for yielding sub-100 nm resolution the way visible optics does.

The reported articles of optical implementation to obtain selective detection of frequency components for reflective FPM are categorized into two methods- aperture scanning and light source scanning. The aperture scanning is to move an aperture in the collection optics between the objective lens and the detector, to collect partial frequency selectively.^{11,37} Applying the approach to DUV FPM imposes high energy fluence on the illumination optical path and thus causes fatal damage to the sample of nanostructures. The light source scanning is to control the illumination angle by transversely moving the position of the light source projected on the back focal plane of the objective lens. It is demonstrated by using light sources, such as a single LED,^{18,38} an LED array,^{31,39,40} or a fiber-coupled coherent laser,⁴¹ which are easy for changing the position. However, this approach is not suitable for reflective DUV FPM because there is no mobile DUV light source or DUV fiber with high solarization threshold.

To address these issues for reflective DUV FPM, we use an aperture scanning illumination system based on the epi-illumination FPM¹⁸ and our previous scatterfield microscopy,^{32,42,43} in which an aperture moves at the conjugate back focal plane (CBFP) of the objective lens to generate high angle illumination at the sample, to avoid light flux concentration in the illumination optics, and to achieve sufficient fluence for low-noise images for DUV FP reconstruction. This paper reports the first reflective DUV FPM implemented using an ArF excimer laser with a wavelength of 193 nm and a high NA catadioptric objective to reconstruct high-resolution images of sub-100 nm multiline patterns on a MoSi photomask. High-resolution images with aperture-scanned illumination beams are reconstructed using an image reconstruction process based on the embedded pupil function recovery (EPRY) algorithm.²⁹ The FP reconstruction algorithm is evaluated in terms of the modulation transfer function (MTF), image updating sequence, and regularization.

II. APERTURE SCANNING ILLUMINATION

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Figure 1 shows the schematic of the DUV FPM optics using the aperture scanning illumination that enables high angle illumination beam at the target. A source (S) is magnified by the lens group (L_S) to form a conjugate back focal plane (CBFP) at which a



FIG. 1. Schematic of aperture scanning illumination for reflective DUV FPM. S: source plane, SA: scanning aperture, BS: beam splitter, OL: objective lens, CCD: charge-coupled device, BFP: back focal plane of OL, CBFP: conjugate back focal plane to BFP, d: SA distance from CBFP center, L_S: lens group for relaying S to CBFP, L_R: lens group for relaying CBFP to BFP, L_T: tube lens, F_d and F_b : back focal lengths of L_R and OL, F_r and F_f : front focal lengths of L_R and OL, and F_T : focal length of L_T.

scanning aperture (SA) is placed so that a transmitted divergent beam is transformed to an angular illumination beam at the target plane by a bi-telecentric optics consisting of the lens group (L_R) and the objective lens (OL), which were designed for 193 nm scatterfield microscopy.⁴² The CBFP size is large enough for locating the SA with an appropriate accuracy, while preserving high telecentricity. Assuming that the CBFP and the target plane are telecentric, the illumination angle (θ) with respect to the SA distance from the CBFP center (d) is defined by focal lengths F_d , F_r , F_f of L_R and OL as

$$\theta(d) = \arcsin \frac{1}{\sqrt{\left(F_f/(d \cdot M)\right)^2}},\tag{1}$$

where the magnification between CBFP and BFP is $M = F_r/F_d$. Once the angular illumination beam is incident on the target, the scattered light containing the target structure information with respect to the incident angle is collected at the charge-coupled device (CCD) by the tube lens (L_T), and the imaging magnification is determined by the focal lengths F_T , F_f of L_T and OL.

III. EXPERIMENTS

A. Implementation of reflective DUV FPM

Figure 2 illustrates the experimental setup of the reflective DUV FPM equipped with the aperture scanning illumination system. The optics used for the ArF excimer laser light (193.3 nm wavelength, 0.3 nm linewidth, 10 ns pulse width, 200 Hz repetition rate, and 15 mJ maximum energy) employed in this system is designed for less energy concentration in the optical paths to avoid the creation of plasma, which would result in a shock wave and damage to the optical elements.²⁷ The optical path is sealed and filled with nitrogen gas to prevent optical power loss caused by light absorption from oxygen in the air, which also generates ozone gas. The rectangular output beam of the 193 nm excimer laser is transformed to a circular beam with enlarged size by a cylindrical lens pair (CL) and shaped to an extended source by a rotating diffuser (RD) placed on a vibration isolation plate (IB), which also removes speckle patterns caused by the laser coherence.³² An effective source (ES) with 3 mm diameter is formed by a lens group (LES) to fit an effective incident NA of the aperture scanning illumination optics. A lens group (L_{CBFP}), with a magnification of about 3.9, transfers the ES to the CBFP of diameter of about 11.7 mm, which is large enough to implement aperture scanning for discrete angular illumination. The aperture scanning illumination optics consists of a relay lens group (L_R) and a catadioptric objective lens (OL). A divergent beam passing through the SA at the CBFP is transferred to the back focal plane of the OL with a magnification of 0.34 and is transformed to an angular illumination beam at the target plane by an angle defined in Eq. (1).⁴² An SA of 1 mm diameter mounted to a two-axis stage (T_{CBFP}) is discretely scanned on the CBFP along circles with diameters 3.7, 7.1, and 10.1 mm to form 16 angular illuminations for each circular scan, yielding 48 angle-scanned images at the charge-coupled device (CCD_I) plane with a non-uniform scan pattern that ensures stable convergence in the FP reconstruction.⁴⁴ A 193 nm catadioptric



FIG. 2. Experimental setup of reflective DUV FPM. M: mirror, CL: cylindrical lens pair, BA: beam shaping aperture, RD: rotating diffuser, IB: vibration isolation plate, ES: effective source, CBFP: conjugate back focal plane, L_{ES} : lens group to form ES, L_{CBFP} : lens group to form CBFP, SA: scanning aperture, T_{CBFP} : stage for aperture scanning, L_R : relay lens group, FS: field stop, BS: beam splitter, OL: catadioptric objective lens, T_{TAR} : target stage, L_T : tube lens, L_F : Fourier plane lens, CCD_F , CCD_I , CCD_N : charge-coupled devices for Fourier plane, imaging, and navigation, FM: fip mirror, OL_N : objective lens for navigation, LED: fiber-coupled light emitting diode source.

objective lens (Corning Tropel, microCAT Panther) with a working distance of 8 mm and an effective NA of 0.13-0.74 is used as OL for both illumination and collection.⁴⁵ The missing frequency components less than NA = 0.13 are recovered by extending frequency bands shifted with the illumination angles using the FP reconstruction algorithm. Angle-scanned beams reflected at the target plane are collected at the charge-coupled devices for imaging or Fourier planes (CCD_I, CCD_F) by a tube lens (LT) or a Fourier plane lens (L_F) selectively using a flip mirror (FM). Images are captured by CCD cameras (Hamamatsu C8000) with 640 \times 480 pixels, 14 μ m pixel size, and a quantum efficiency of 60% at 193 nm. The light scattered at the target is imaged through the collection optics with a magnification of 350 because of which the pixel size and area of CCD_I correspond to 40 nm and 25.6 \times 19.2 μ m² at the target plane, respectively. The Fourier images collected at CCD_F are used for the illumination angle calibration by placing a plane mirror at the target plane. A navigation microscope with low resolution and large field of view, consisting of a navigation objective lens (OL_N), a visible charge-coupled device (CCD $_{\rm N}),$ and a fiber-coupled visible light emitting diode (LED), is used to locate the target in the field of view of OL by the target stage (T_{TAR}) with six axes, because the non-standard OL is fixed above the target plane with a small field of view. All imaging devices and stages are connected to and controlled by a processing computer for the FPM measurement procedure.

Compared to aperture scanning methods in recent FPM illumination systems, ^{37,46,47} the aperture scanning illumination scheme in this DUV FPM avoids light energy concentration that causes damage to nanoscale features. The aperture diameter is determined at 1 mm by empirically considering the optimized energy and spatial coherence of the illumination beam. The energy fluence from the laser source to the CCD_I and CCD_F is optimized while considering sufficient intensity for imaging as well as damage thresholds of the coatings of optical components and targets. The tile size for the FP recovery process is 30 pixels, which is determined by the spatial coherence length of 1.2 μ m calculated from $l = 1.22\lambda z/w$, where λ , *z*, and *w* correspond to the wavelength of light, propagation length, and diameter of the illumination source, respectively.¹⁵

The significant background intensity of each raw target image caused by stray lights is removed using the background image taken without the target. Subtracting the background image at each illumination angle from the raw target image generates the low resolution input images for the FP reconstruction process, ensuring convergence to and divergence from the local minima during the recovery.

A series of molybdenum silicide (MoSi) multilines on a silica substrate fabricated by e-beam lithography are used as the target for the DUV FPM experiments, as shown in Fig. 3. The targets have periodic line structures with a duty cycle of 0.5, a height of 73.8 nm, and 12 linewidths of 80–800 nm. The spatial frequencies corresponding to the linewidths are used for the characterization of the DUV FPM metrology in terms of the modulation transfer function (MTF).

B. FP reconstruction process

The amplitude and phase of the target are reconstructed using the Embedded Pupil Function Recovery (EPRY) algorithm, in which both the initial frequency spectrum and pupil function are updated



FIG. 3. Specifications of multiline targets on the MoSi photomask. (a) Target structure: MoSi multiline on silica substrate with duty cycle = 0.5, height = 73.8 nm, and various linewidths, Ws. (b) Linewidths and corresponding spatial frequencies.

repeatedly through frequency filtering and intensity replacement while alternating between the frequency domain and spatial domain for all input images with illumination angles.²⁹ The initial spectrum $S_0(u)$ for upsampling to the high-resolution image is prepared by averaging the 48 input images. The initial pupil function $P_0(u)$ is set to an annular band-pass filter having lower and higher frequency limits of $k_0 \times NA_{\max or \min}$, where k_0 is the wavenumber, according to the annular intensity distribution at the back focal plane formed by the central obscuration of the objective, as shown in Fig. 4(a). The updating process follows (2) and (3), where $\emptyset_n(u) = P_n(u)S_n$ $(u - U_n)$ and $\emptyset'_n(u)$ represent the exit wave at the pupil plane shifted by the illumination wavevector U_n and the exit wave updated by imposing the intensity constraint for angular illumination number n, respectively,

$$S_{n+1}(u) = S_n(u) + \frac{|P_n(u+U_n)|}{\max|P_n(u+U_n)|} \frac{P_n^*(u+U_n)}{|P_n(u+U_n)|^2 + \delta} \times [\emptyset'_n(u+U_n) - \emptyset_n(u+U_n)],$$
(2)



FIG. 4. Fourier plane images for illumination angle measurement. (a) Back focal plane image of OL without scanning aperture at CBFP. Maximum and minimum NAs of the OL are 0.74 and 0.13, respectively. (b) Image overlapped with 48 illumination beams made by scanning SA at CBFP. (c) Segmentation for calculating central positions of illumination beams. (d) Recovered spatial frequency spectrum using measured illumination angles.

$$P_{n+1}(u) = P_n(u) + \frac{|S_n(u - U_n)|}{\max|S_n(u - U_n)|} \frac{S_n^*(u - U_n)}{|S_n(u - U_n)|^2} \times [\mathscr{O}_n'(u) - \mathscr{O}_n(u)].$$
(3)

The symbols * and δ denote the complex conjugate and regularization constant for noise tolerance,²¹ respectively. The step size for updating the target spectrum is the ratio of the amplitude to the maximum.⁴⁸ The updating process for the 48 angular illuminations is iterated until the high-resolution output image quality does not improve further with a constant convergence index G_i defined by

$$G_{i} = \sum_{n} \sum_{x,y} abs (A_{n,i}^{t} - A_{n}^{m})^{2}, \qquad (4)$$

where A_n^m and $A_{n,i}^t$ are the amplitude of the input image with the *n*th illumination angle and the updated image produced from the updated spectrum during the *i*th iteration process for the pixel indices x and y in the images.

From the second iteration, the input image is multiplied by the intensity correction factor defined by $c_i = \sum_{x,y} I_{n,i}^t / \sum_{x,y} I_{n,i}^m$, where $I_{n,i}^t$ and $I_{n,i}^m$ are the updated image and the input image for *n*th illumination angle and *i*th iteration, thereby correcting the non-uniform intensity distribution of the light source.⁴⁹

C. Illumination angle measurement

Stitching the input images in the frequency domain requires accurate illumination angle input for output image recovery with less distortion.^{50,51} The angle value is obtained from the image of the CBFP scanning aperture projected at a conjugate plane of the objective's BFP in the collection path, which is the Fourier plane of the target plane, through a mirror reflection at the sample plane. The bi-telecentric optics for projecting the CBFP aperture in the collection path is optimized for distortion, yielding reliable measurement of the allumination angle, which is converted from the position of the aperture image.⁴² The scanning aperture image is captured by the DUV CCD camera at the Fourier plane.

Figure 4 shows the Fourier plane images of the scanning aperture at the CBFP for obtaining the illumination angle. The Fourier plane image with full-angle illumination is used to find the projection ratio with respect to the CBFP size, which is used to calculate the NA of the illumination beam, as shown in Fig. 4(a). The aperture images for 48 positions at the CBFP are captured and overlapped as shown in Fig. 4(b), and then segmented to obtain the central positions, as indicated by the red circles and blue dots in Fig. 4(c). These position values are converted to NA values using a conversion relation between pixel index and Δ NA per pixel. The NA difference per pixel is calculated from the maximum NA of the objective at the Fourier plane boundary and the pixel numbers from the center. These NAs are converted to spatial frequency values for stitching the 48 input images to recover an extended frequency spectrum in the frequency domain in Fig. 4(d). They are then used to reconstruct a high-resolution target image.

IV. RESULTS AND DISCUSSION

A. Image reconstruction

The images of the multilines with linewidths of 80-800 nm are reconstructed using the FP phase retrieval algorithm described above and compared with conventional reflective DUV microscopy as shown in Fig. 5(a). The upper two rows are the images using conventional microscopy with the full illumination NA, and the lower



FIG. 5. Contrast evaluation of reconstructed images. (a) Images of multilines on MoSi photomask obtained by conventional microscopy and DUV FPM. Red-colored square portions in upper images are enlarged in lower images. Linewidths are 600, 300, 160, 120, 100, 90, and 80 nm, respectively. Scale bar indicates 5 μ m. (b) Relative modulation transfer functions (MTFs) for conventional microscopy and FPM. (c) Contrast enhancement ratio of FPM with respect to conventional microscopy.

two rows show the FPM with angle-scanning illumination, demonstrating the contrast enhancement, as the linewidth is increasingly narrowed. For a quantitative comparison between the two, the images are evaluated by relative MTF, which is referenced to the contrast of the image of the 800 nm multiline and obtained from the amplitude of the fundamental modulation frequency. Figure 5(b) shows the relative MTF calculated from the Fourier transform of the intensity profile in the modulation direction of the multiline images and fitted using an exponential function. From the values, the contrast enhancement ratios of DUV FPM relative to conventional microscopy are calculated as shown in Fig. 5(c). The enhancement ratios are around 1.2 for a range of 120–180 nm, while they are exponentially increased up to 6 for a range of 80–100 nm.

According to the Sparrow resolution limit,¹⁵ the theoretical resolution limits of the incoherent DUV microscopy and DUV FPM are calculated at 114 nm with $R = 0.44\lambda/NA$, and at 88 nm with $R = 0.68\lambda/(2NA)$, for $\lambda = 193$ nm and NA = 0.74, respectively,

showing that FPM improves resolution by 26 nm compared to conventional microscopy. The experimental image comparison shown in Fig. 5(a) is consistent with the theoretical calculation as the clearly resolved images appear at 100 and 80 nm for conventional and FPM imaging, respectively. The relative MTF comparison and enhancement ratios shown in Figs. 5(b) and 5(c) demonstrate that the contrast enhancement effect of the DUV FPM is manifested around the resolution limit and that the resolution can be improved beyond the theoretical limit of conventional microscopy. The extended optical transfer function of the FPM can account for this dramatic improvement at high spatial frequency.¹⁸

B. Input image order

One of the parameters that affect the condition for the best recovered image in the FP reconstruction process is the input image order, which determines whether the starting point settles



FIG. 6. Comparison of input image order between illumination NA order and total energy order. (a) and (b) Convergences for targets of 800 and 80 nm. (c) Reconstructed amplitude and phase images obtained using the two ordering methods. Scale bar indicates 1 μ m.



FIG. 7. Contrast dependence of recovered image on regularization parameter δ . (a) Recovered images parameterized with δ , where scale bar indicates 5 μ m. (b) Intensity profiles along red dotted lines of (a). (c) Contrast variation with respect to regularization parameter.

on a local minimum or the global minimum.44,52 Two ordering methods--illumination NA and total energy--are compared with respect to target linewidths of 800 and 80 nm. The former method arranges the images from lowest to highest illumination NA, while the latter arranges them from highest to lowest energy. Figures 6(a)and 6(b) show the convergence curves as the mean squared error (MSE) vs iteration number, which shows the difference between the ground truth and the estimated image, and Fig. 6(c) shows the reconstructed amplitude and phase images. For the 800 nm target, the MSE converges to zero in the same manner using both methods, resulting in slight noise differences in the images. However, for the 80 nm target containing higher spatial frequency components than the 800 nm target, the convergence curves are different, with two large non-zeros, resulting in an obvious difference in image quality. The total energy order method produces higher image quality for both targets with lower and higher spatial frequencies. These results imply that the total energy order is useful for better reconstruction of the target image with a higher spatial frequency-which is consistent with the previously reported simulation result.44

C. Regularization

The FP reconstruction performance depends on the noise of the input image—such as Poisson noise or speckles generated during the image acquisition.²¹ They are denoised by the regularization parameter δ introduced in Eq. (2) to control noise tolerance, for updating with every input image. The dependence of the contrast of the

recovered image on the regularization is analyzed by varying within $\delta = 30-650$ at an optimized iteration of 20, as shown in Fig. 7. A contrast variation calculated from the intensity profiles in Fig. 7(b) of the images parameterized with δ indicated in Fig. 7(a) is plotted in Fig. 7(c), showing that the contrast increases rapidly until $\delta \approx 150$ and saturates at $\delta \approx 650$.

V. CONCLUSIONS

We implemented a reflective DUV FPM that incorporates an aperture scanning illumination system to accommodate a 193 nm excimer laser and high NA catadioptric objective lens, successfully demonstrating a marked contrast improvement in sub-100 nm imaging compared to conventional DUV microscopy. High contrast images of a series of multilines with a minimum linewidth of 80 nm, which is beyond the theoretical resolution limit for the wavelength of 193 nm used for the experiment, are reconstructed by FP reconstruction procedure. The contrast of the reconstructed image is enhanced by a factor of up to six compared to conventional DUV microscopy, using an advanced FP reconstruction procedure that includes illumination angle measurement, background elimination, optimized input image order, and computational denoising. From the implementation and results, we concluded that the reflective DUV FPM has high capability of optical implementation for sub-100 nm-scale imaging that is lacking in reflective FPMs using visible or EUV light sources. This indicates potential for advanced implementation

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toward applications in nanoscale measurements with a possible super-resolution scheme for semiconductor device metrology.

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Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the equipment or materials identified are necessarily the best available for the purpose.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Kwan Seob Park: Data curation (equal); Formal analysis (equal); Investigation (equal); Software (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). Yoon Sung Bae: Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Software (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). Sang-Soo Choi: Resources (equal). Martin Y. Sohn: Conceptualization (lead); Data curation (lead); Formal analysis (lead); Funding acquisition (lead); Investigation (equal); Methodology (lead); Project administration (lead); Supervision (lead); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (lead).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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