Shape-Optimised TiO_2 Metamaterial Solid Immersion Lenses with Deep-Learning-Assisted Super-Resolution Imaging

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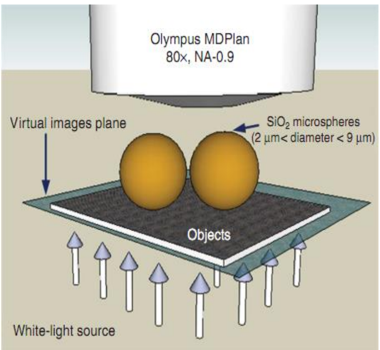

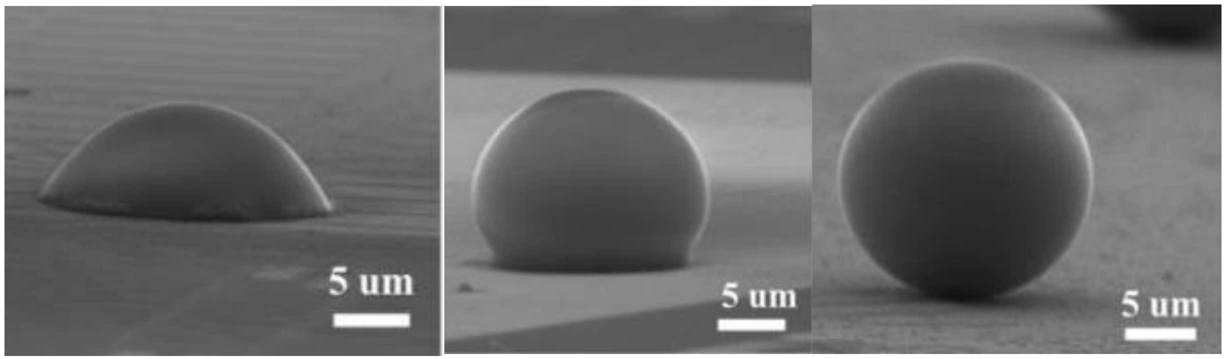

EMRS Fall Meeting, Sept 14-17th, 2026, Poland

Outline

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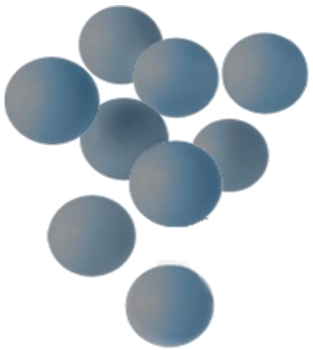
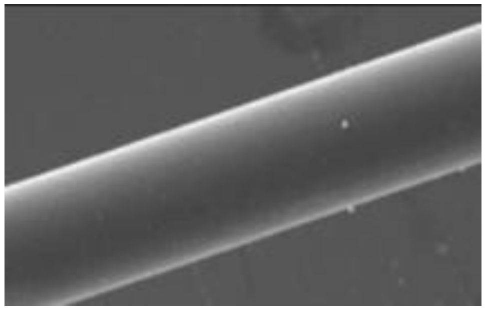
- Mesoscale photonics & microsphere nano-imaging
- TiO_2 metamaterial solid immersion lens (mSIL)
- Shape effect & imaging mechanism
- Digital twin of mSIL imaging
- Conclusions

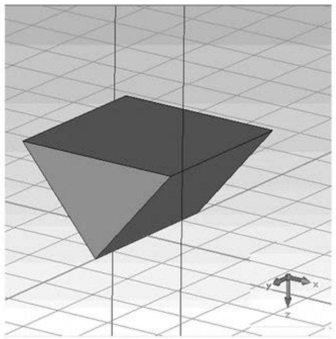
Mesoscale photonics

- **Mesoscale:** effective dimensions are comparable with the incident radiation wavelength.

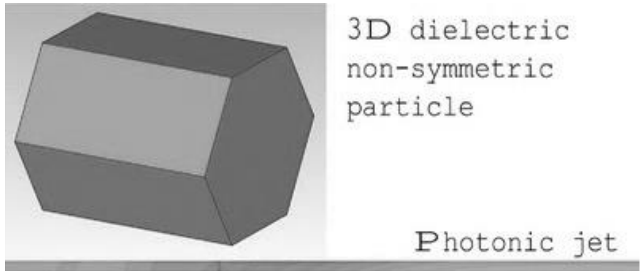
- **Typical:** several to several tens wavelength, e.g. ~2 λ – 100 λ







(a)



Optical Phenomena in Mesoscale Dielectric Spheres and Immersion Lenses Based on Janus Particles: A Review

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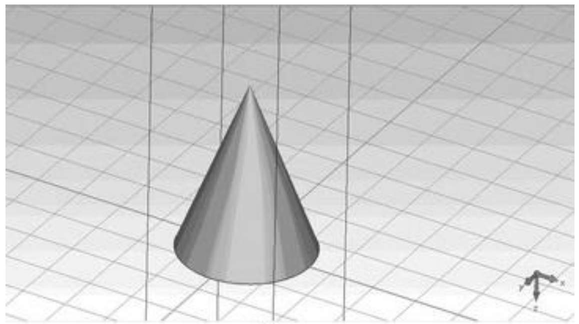
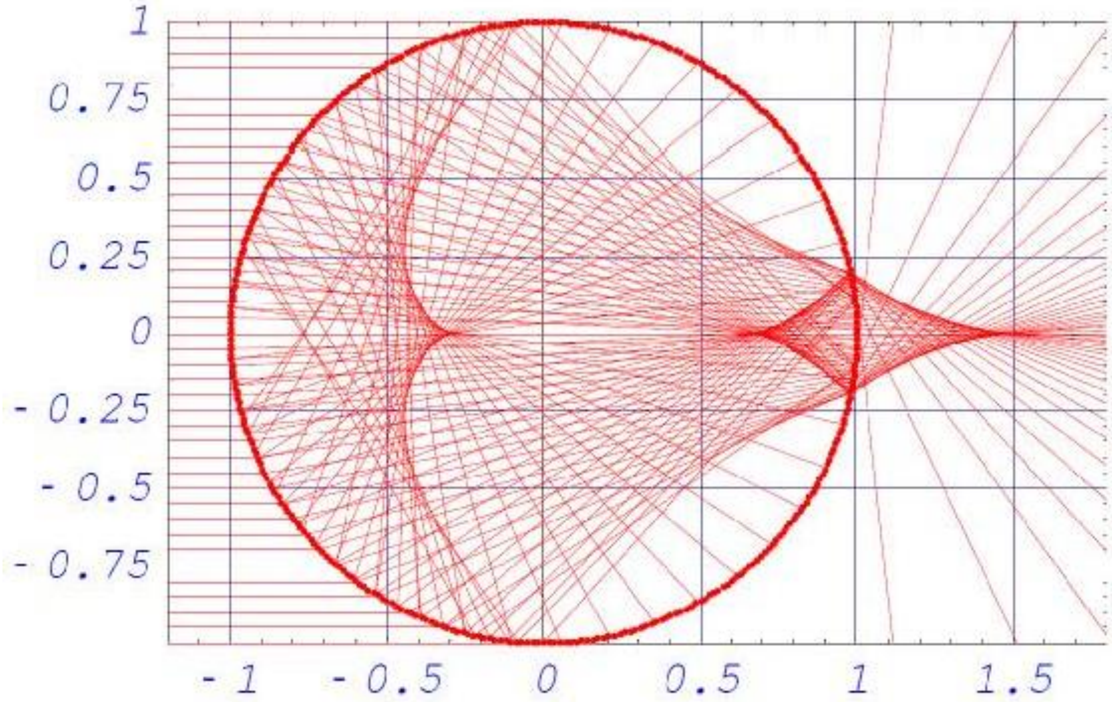
Abstract—The mesoscale optical phenomena in dielectric spheres with a size parameter $q = 2\pi R/\lambda \sim 10$, where R/λ is the particle radius in incident wavelength units, have been considered. These phenomena make it possible to implement microscopy beyond the diffraction resolution limit. Another example of mesoscale optical phenomena is the field localization in immersion lenses based on Janus particles.

Phys. Wave Phenom. ,
30, 217-241 (2022).
30, 293-297 (2022).



(a)

Big particle: Ray tracing (a >>λ)



Spot size (Caustic on sphere)**:**

$$w \approx a\sqrt{\frac{(4-n^2)^3}{27n^4}}$$

Optical Enhancement:

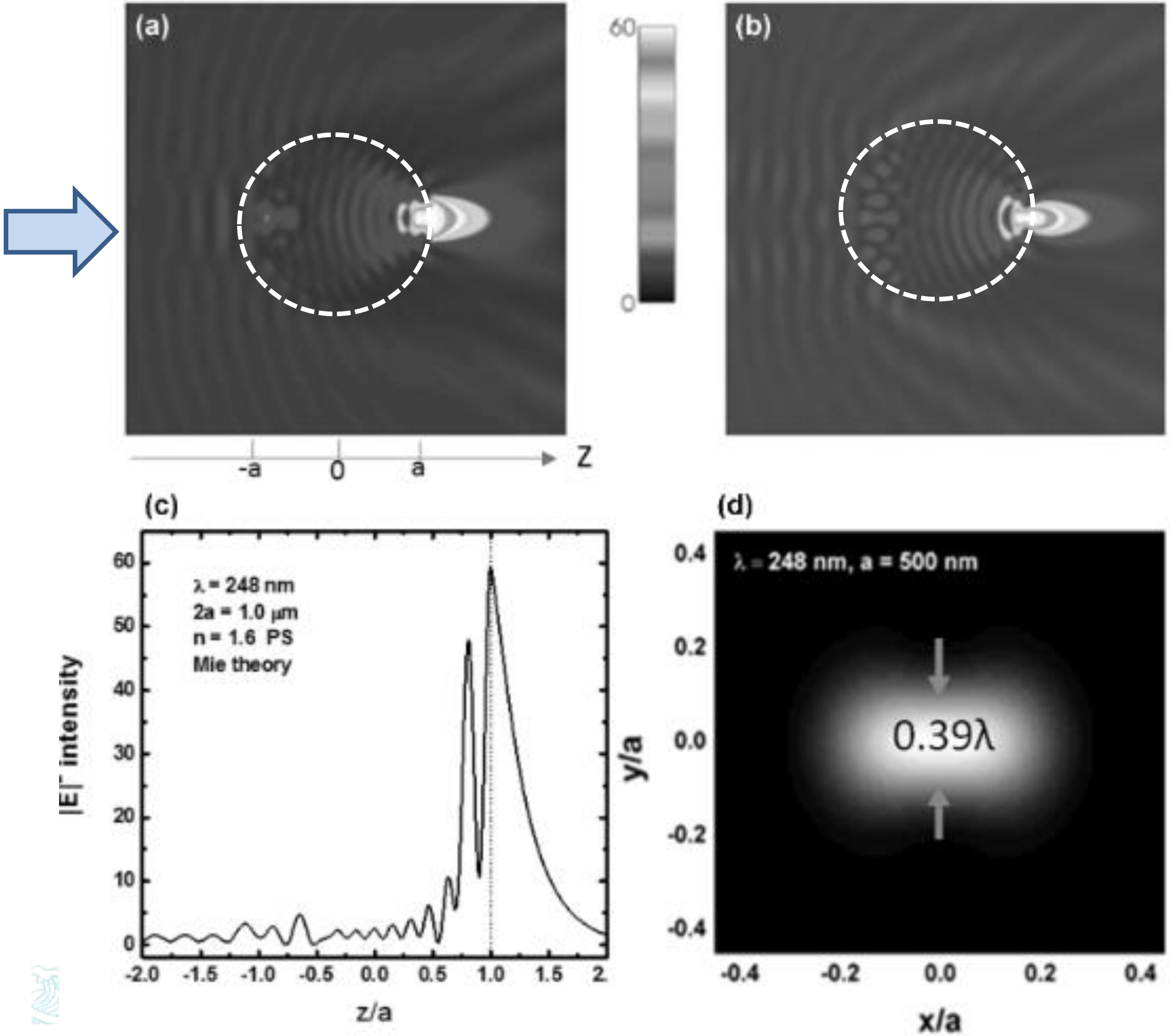
$$\frac{I_m}{I_0} \approx \frac{a^2}{w_g^2} \approx \frac{27n^4}{(4-n^2)^3}$$

Snell's law and energy conservations

$$\theta_t = \arcsin\left[\sin\theta_i / n\right]$$

B. S. Luk'yanchuk, N. Arnold, S. M. Huang, Z. B. Wang, and M. H. Hong, Appl. Phys. A 77, 209-215 (2003).

Small particle: Sub-diffraction focusing

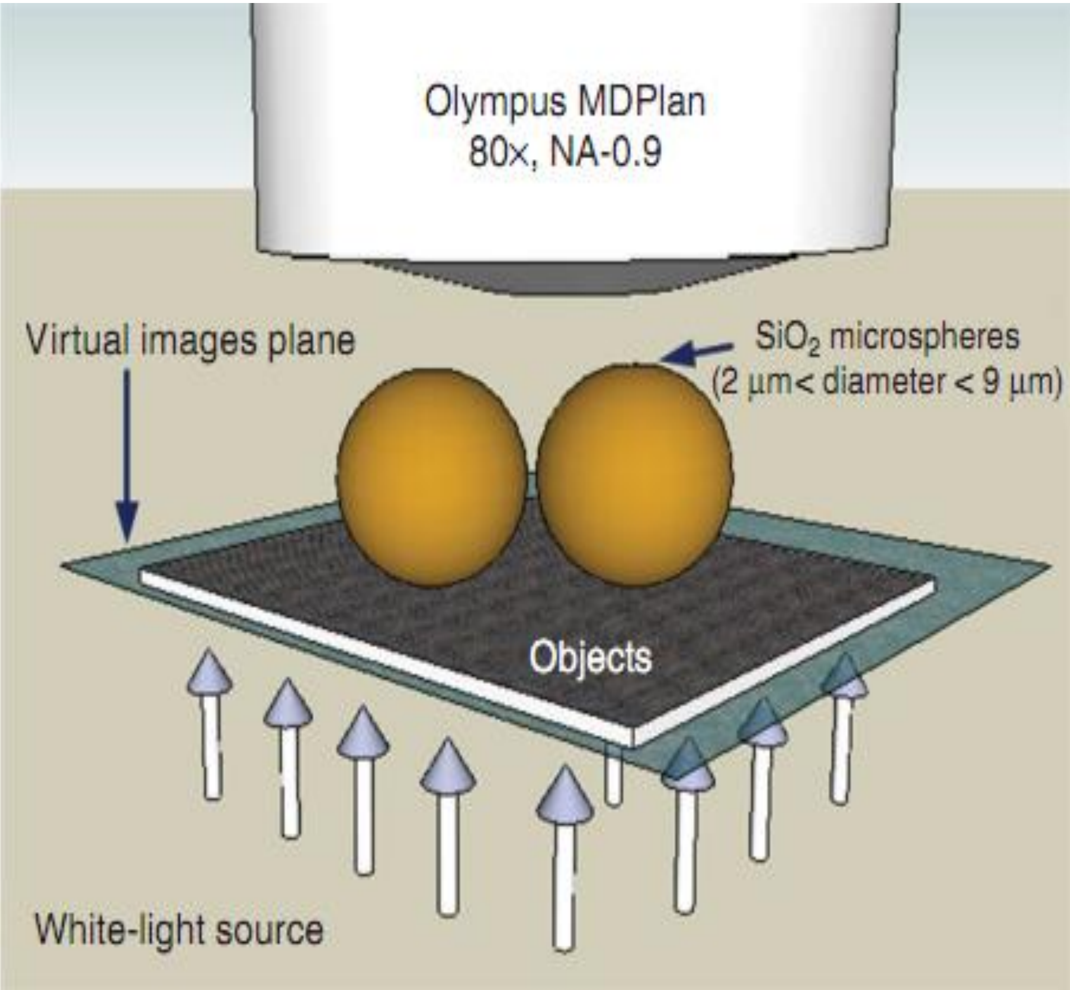


~0.39λ

Photonic Nanojet (PNJ)

Nanoscience, 3, 193-210, DOI: 10.1039/9781782623717-00193 (2016).

Wide-field White Light Microsphere Nanoscope



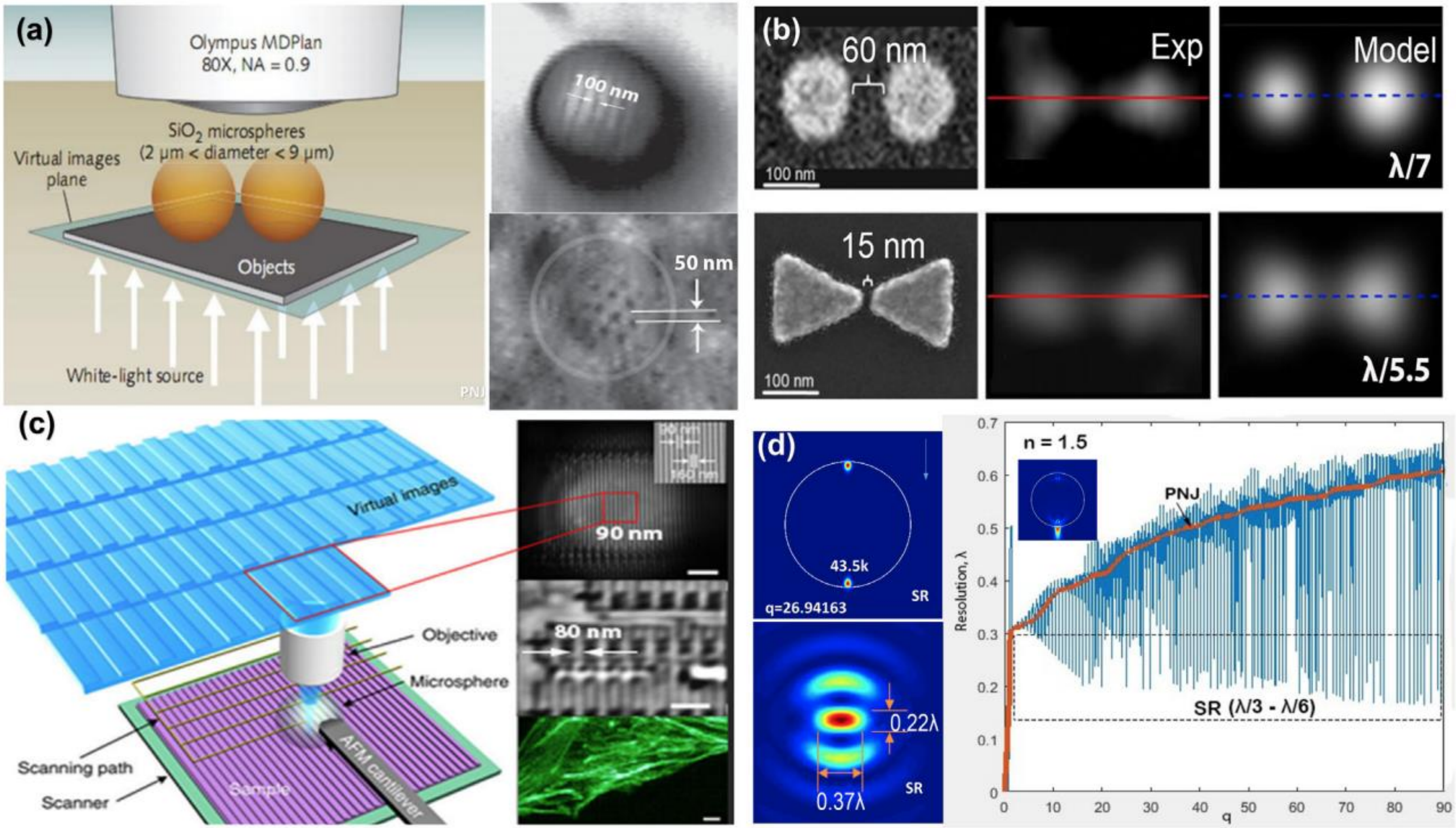
Best Resolution: <u>50 nm,</u> for plasmonic sample

<u>Z.B. Wang</u> et al., ***Nature Communications*** *2, Art. 218, (2011)*

Laser Photonics Rev. ,17, 2200029 (2023)

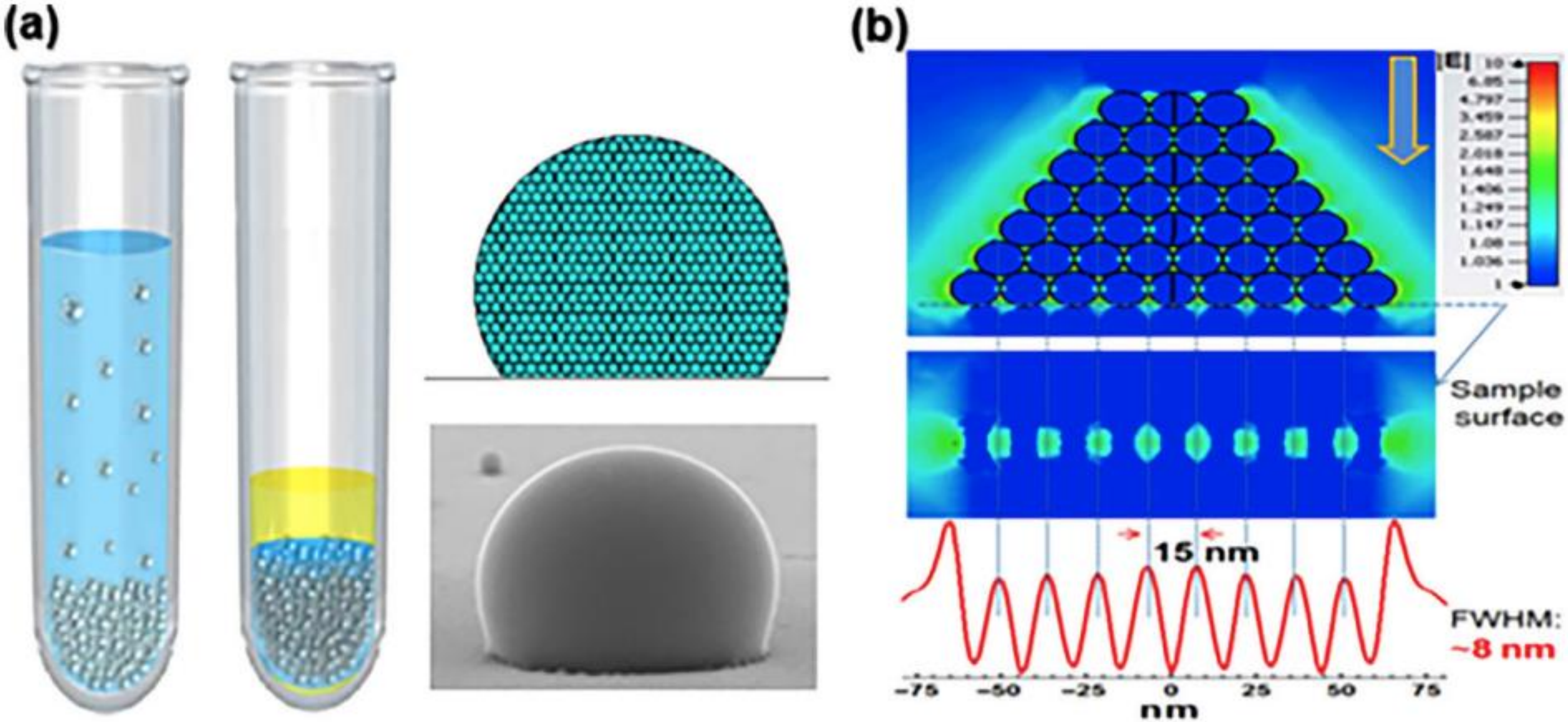
BBC, New York Times, Laser Focus World….

http://www.youtube.com/watch?v=nOtkMoPh4Yw



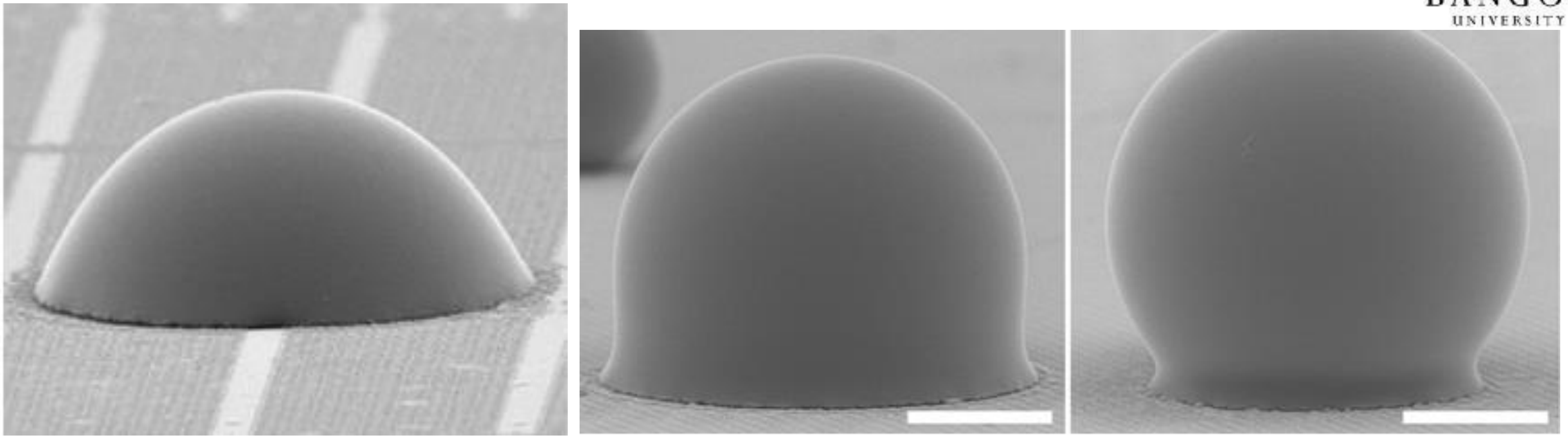
"[Roadmap on Label-free Super-resolution Imaging](#)", ***Laser Photonics Rev.*** ,17, 2200029 (2023)

3D Metamaterial Solid Immersion Lens



Sci. Adv. 2, e1600901 (2016)

Sub-spherical and Super-spherical

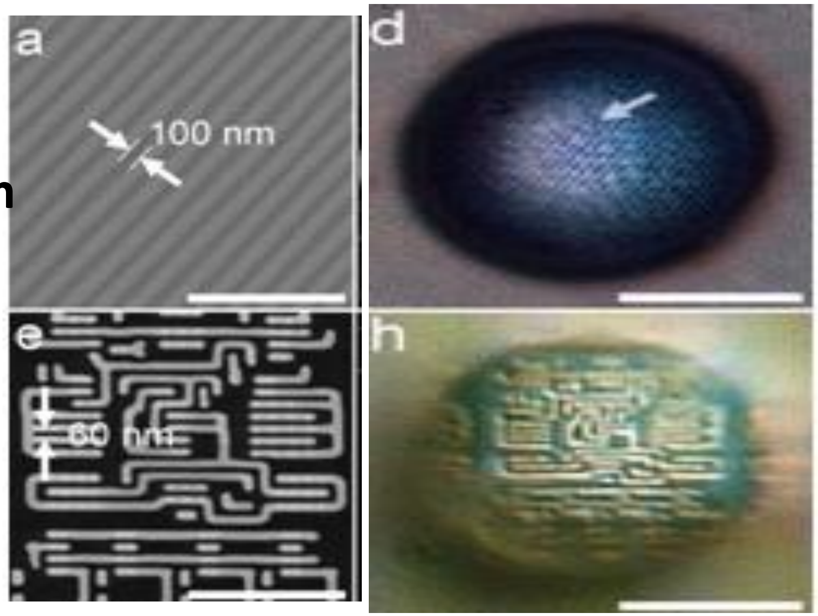


Sci. Adv. 2, e1600901 (2016)

No full spherical shape

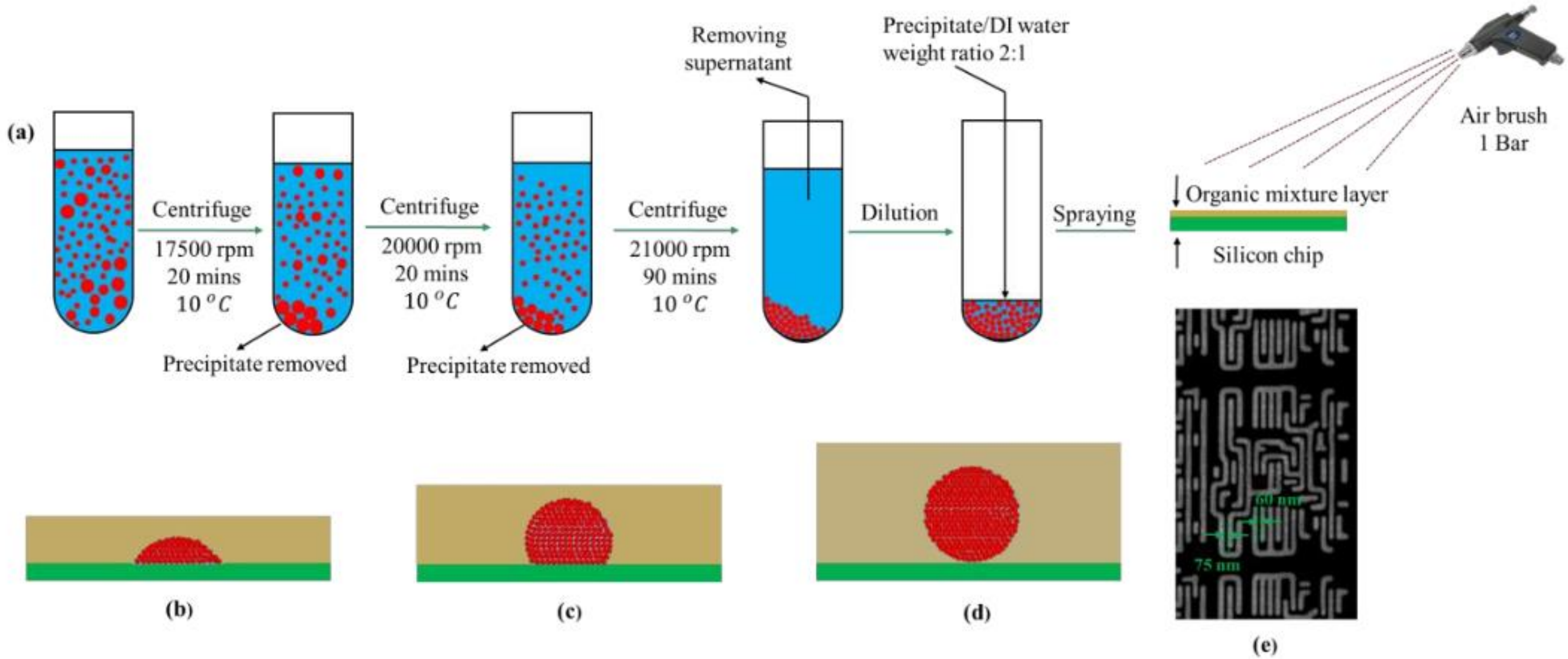
100 nm

60 nm



New protocol:

- 2-step centrifuge to 3-step centrifuge, improving material purity
- Full-sphere shape by controlling organic mixture layer thickness



[Shape-Dependent, Deep-Learning-Assisted Metamaterial Solid Immersion Lens (mSIL) Super-Resolution Imaging](“, *arXiv*:2603.24371 (2026)

Color-effect: R,G,B

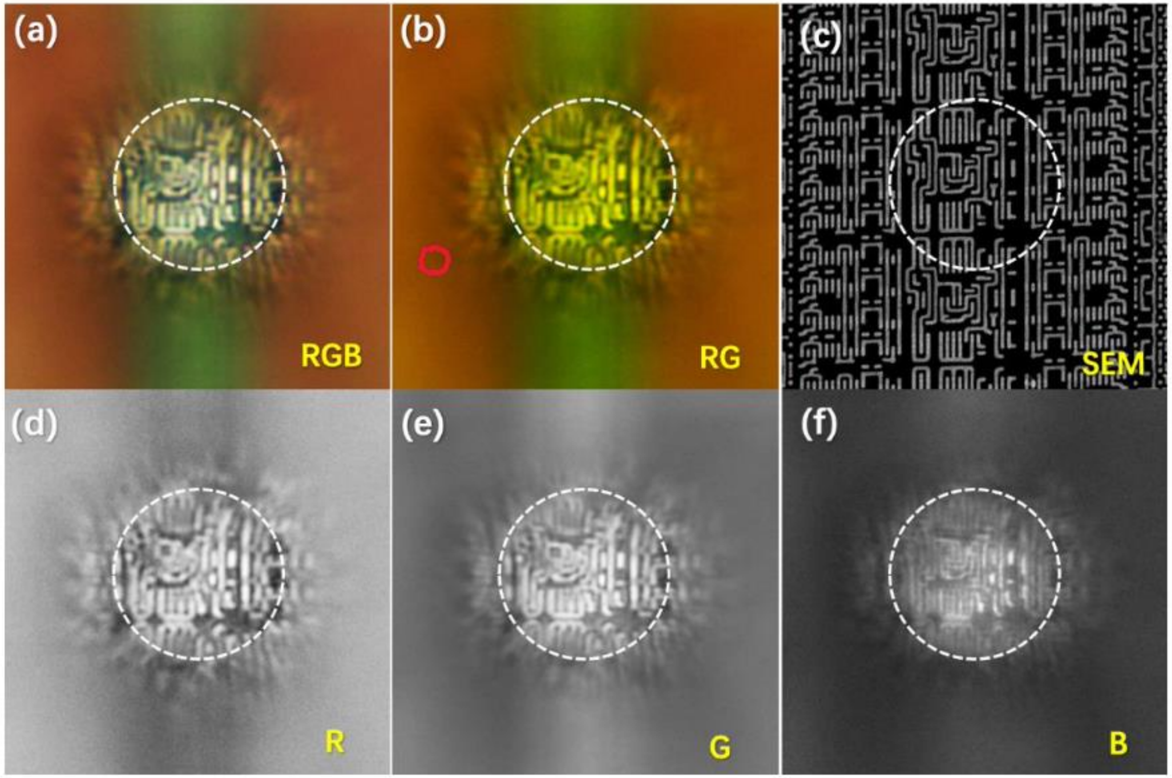


Figure 2 Wide-field imaging of a semiconductor chip using a TiO_2-based super-mSIL lens under white light: (a) RGB image; (b) combined red-green channels; (c) SEM reference; (d–f) individual red, green, and blue channels. Dashed circles indicate regions used for resolution comparison.

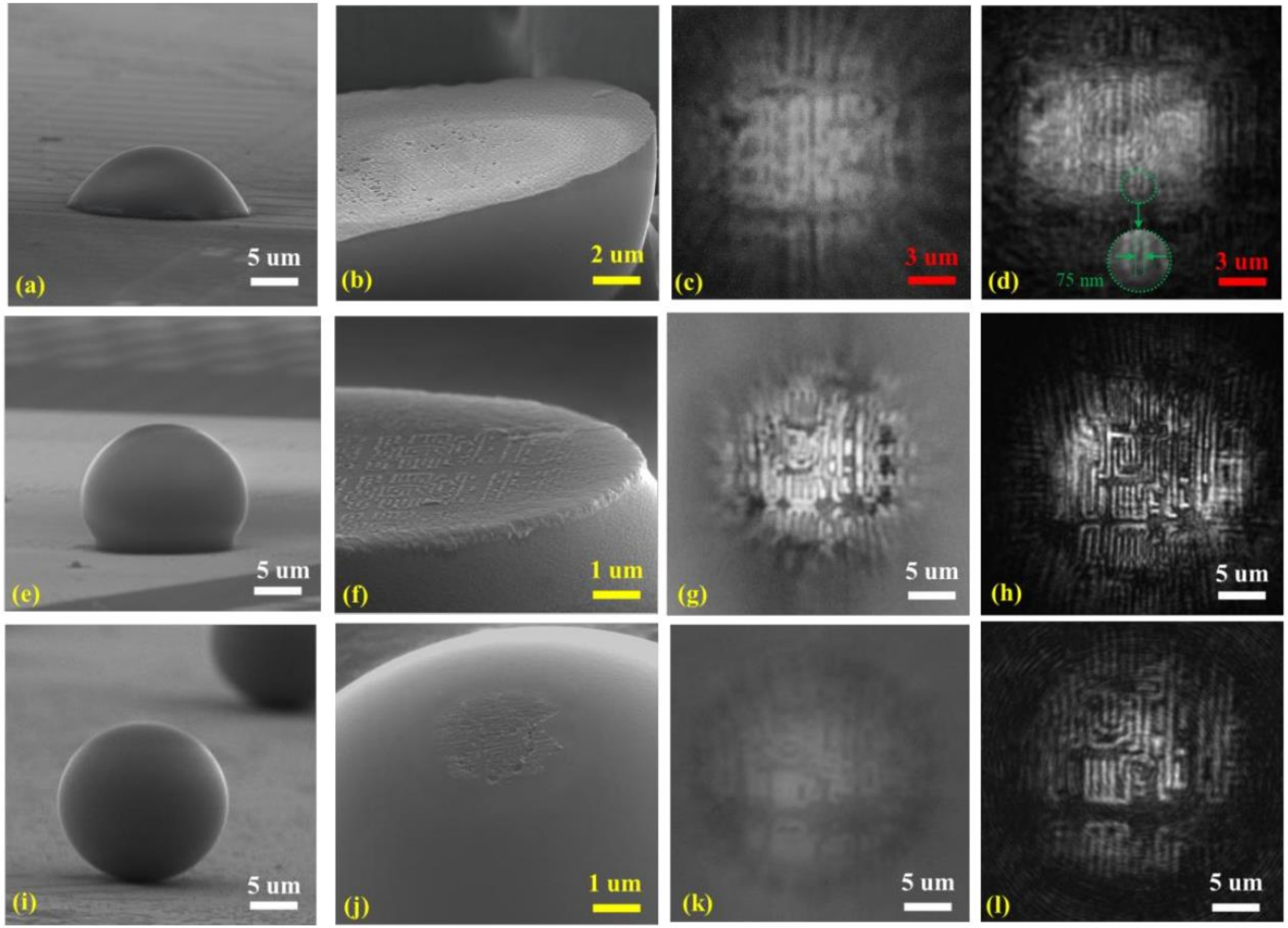
Red channel: best

Shape-effect: sub, super, full

sub-

super-

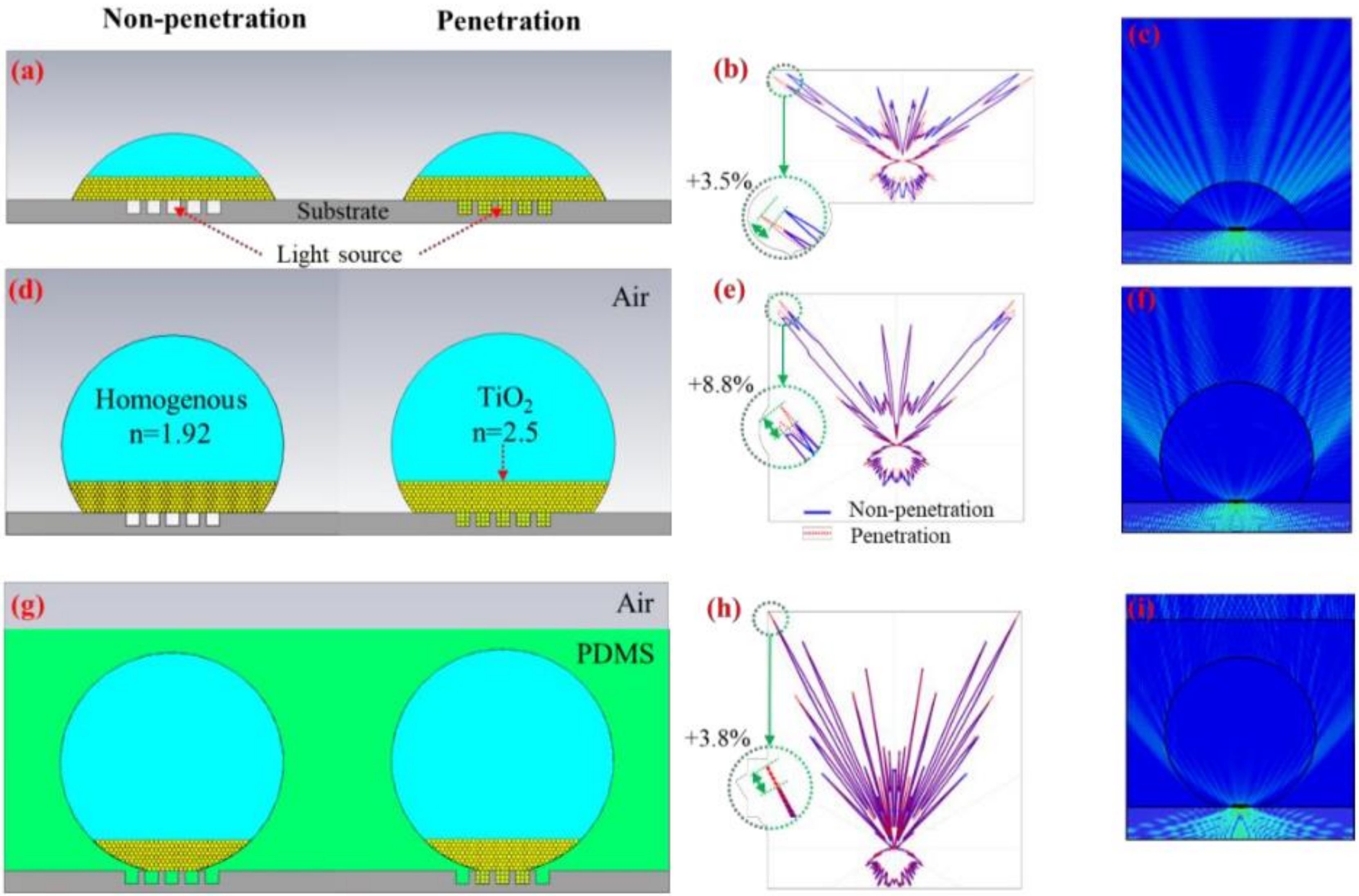
Full-



super-shape: BEST

Figure 3 The SEM images of (a) sub-mSIL, (e) super-mSIL and (i) full-mSIL lenses and their bottom surface characterization (b), (f) and (j), respectively. Wide-field microscopy images, (c), (j) and (k), and laser-confocal microcopy images, (d), (h) and (l) focused on pattern of silicon chip.

Theory by CST Modelling



+3.5%

+8.8%

BEST

+3.8%

Digital Twin by deep-learning

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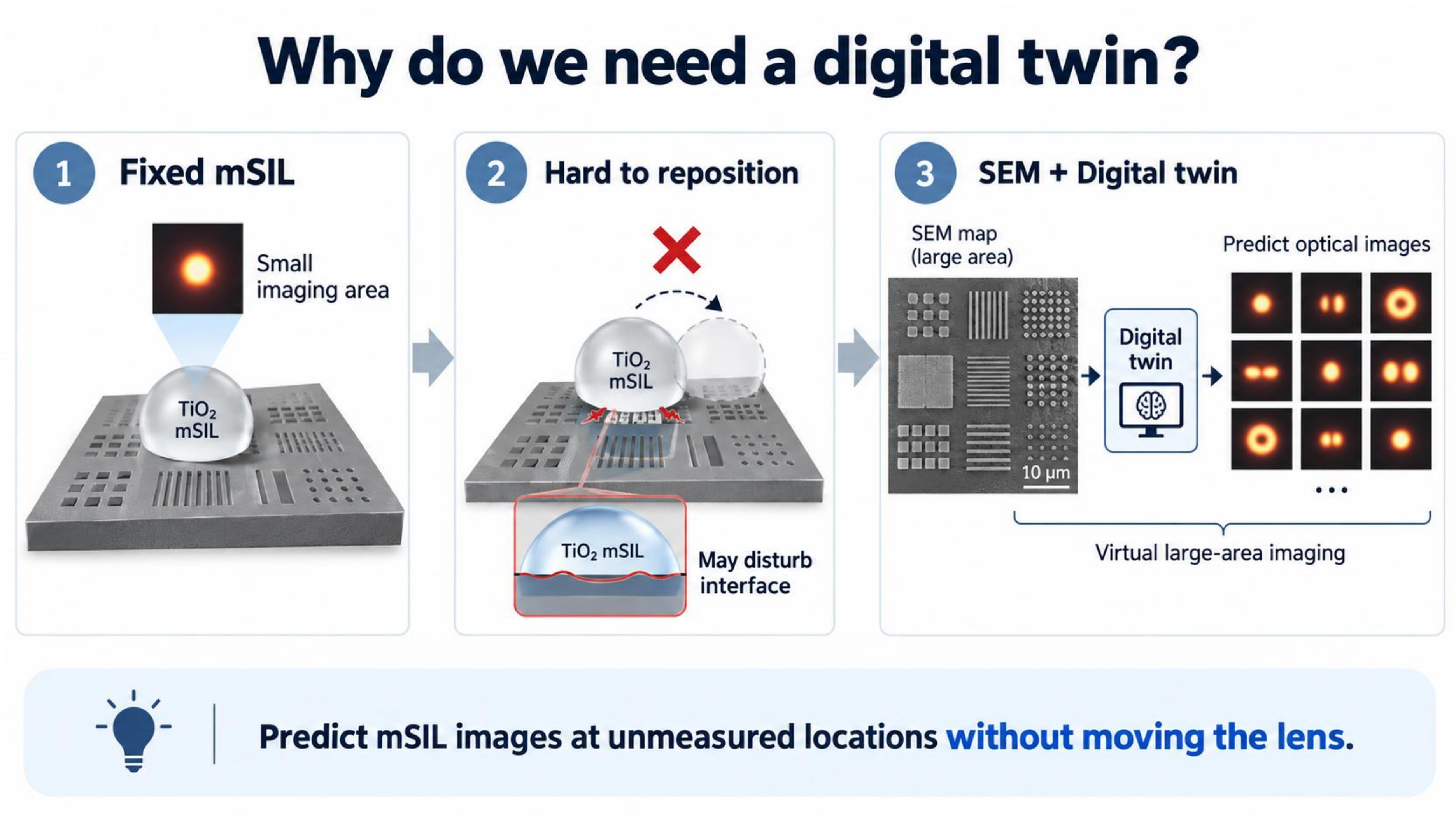


SinCUT: Single-Image Contrastive Unpaired Translation

Learn image-to-image translation from only one image per domain

Domain A (single image)

Input image

SinCUT

Patch-wise contrastive learning

Learn translation from a single image per domain

Domain B (single image)

Translated result

1. Unpaired image-to-image translation
2. Only one image required per domain (single-image training)
3. Preserves local content while changing image appearance

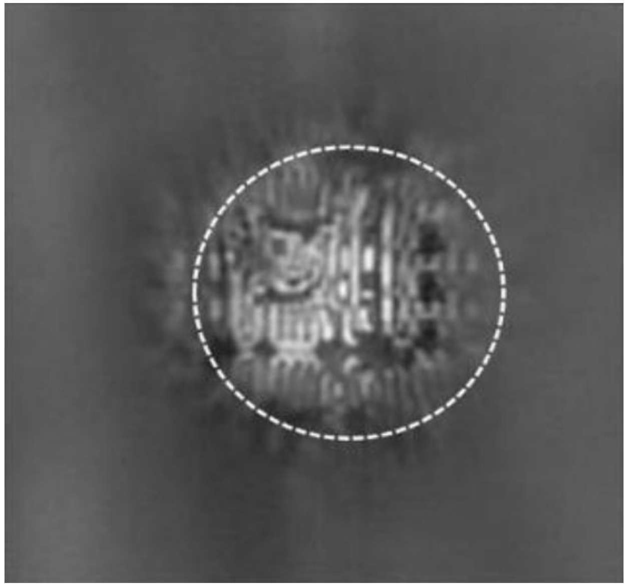
SinCUT can learn meaningful image translation from just one image in each domain.

Source: https://github.com/taesungp/contrastive-unpaired-translation

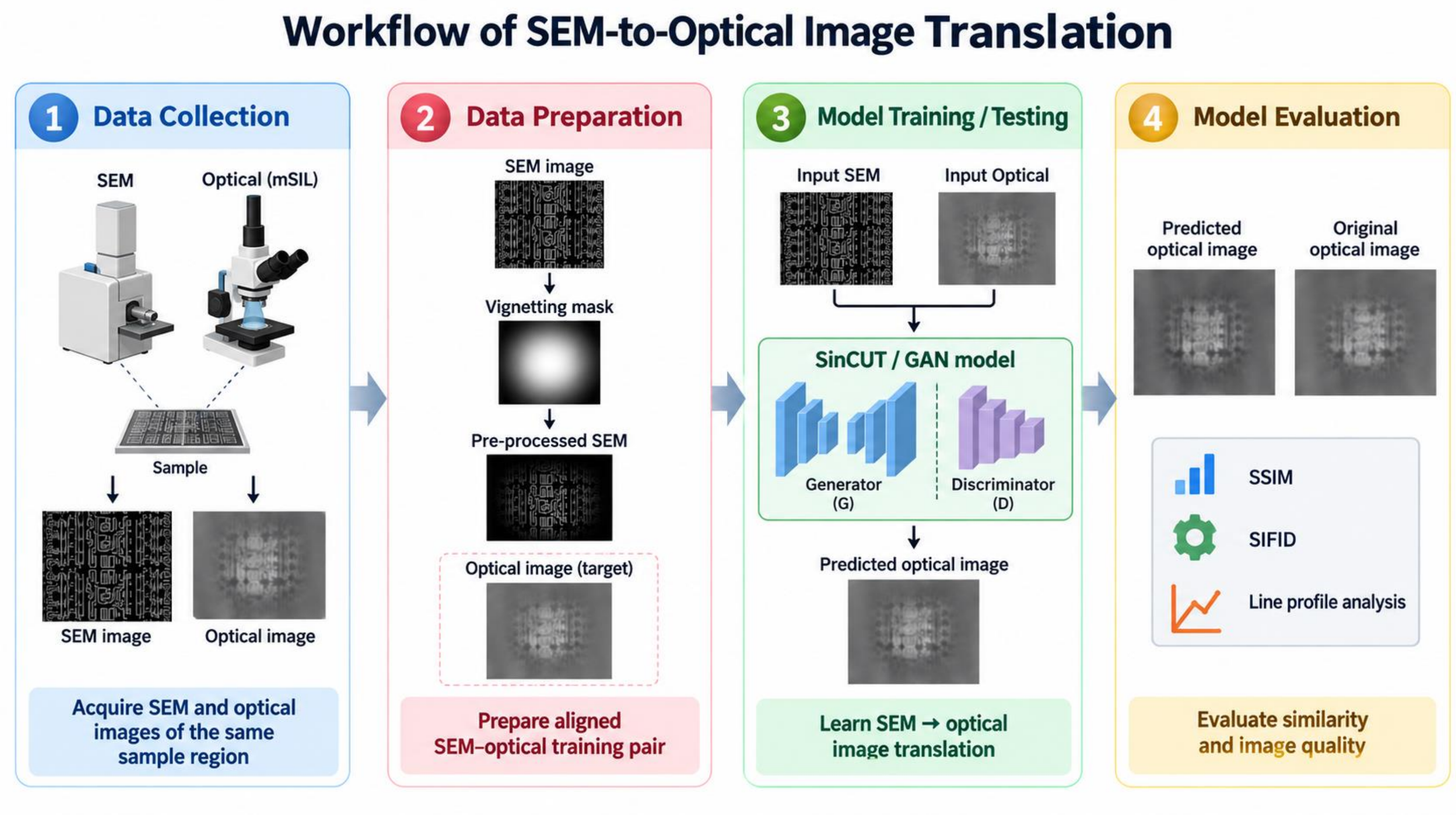
Park et al., ECCV 2020.
Contrastive Learning for Unpaired Image-to-Image Translation.

Domain A: SEM
Domain B: Optical (mSIL)

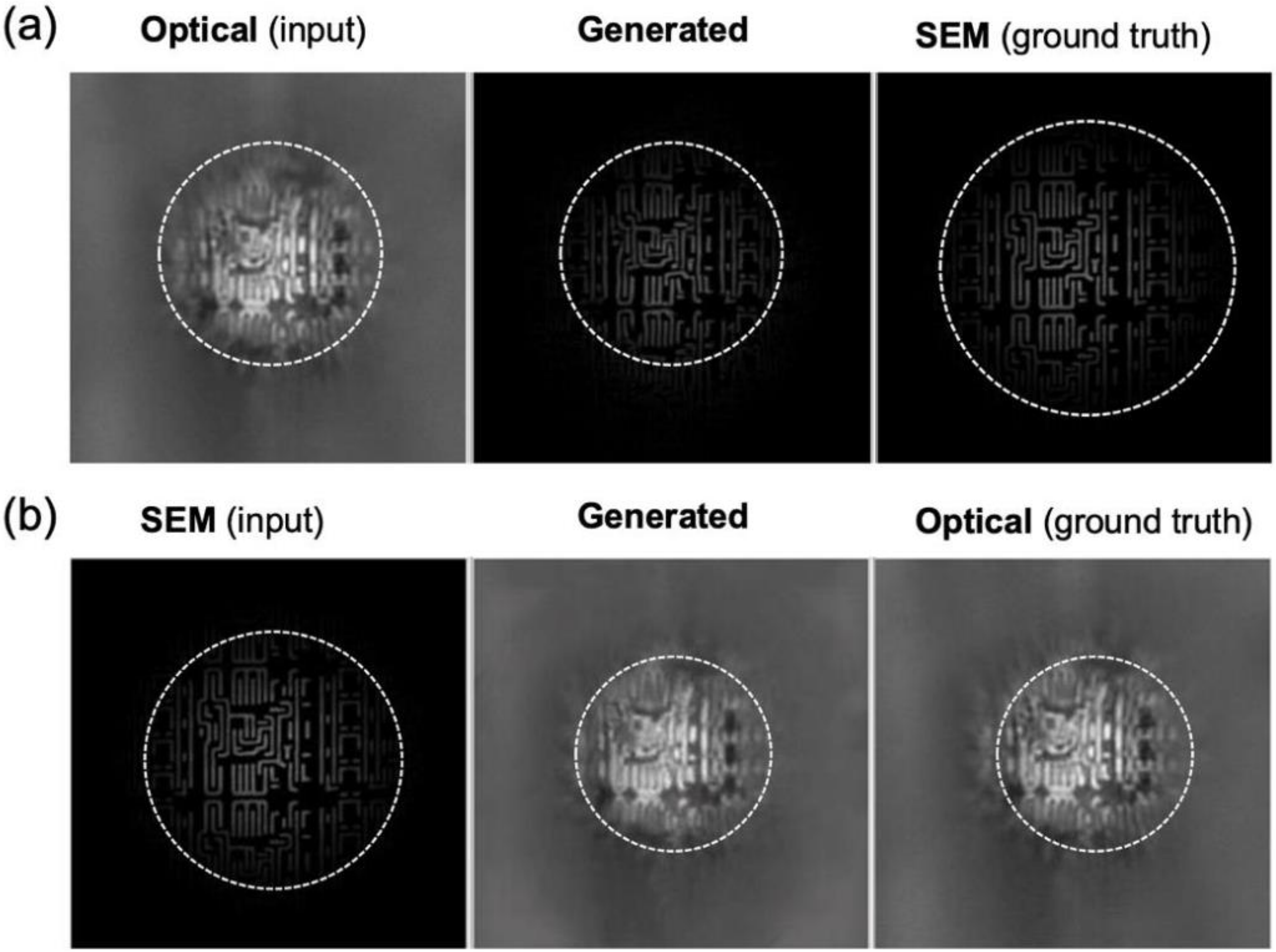
SEM



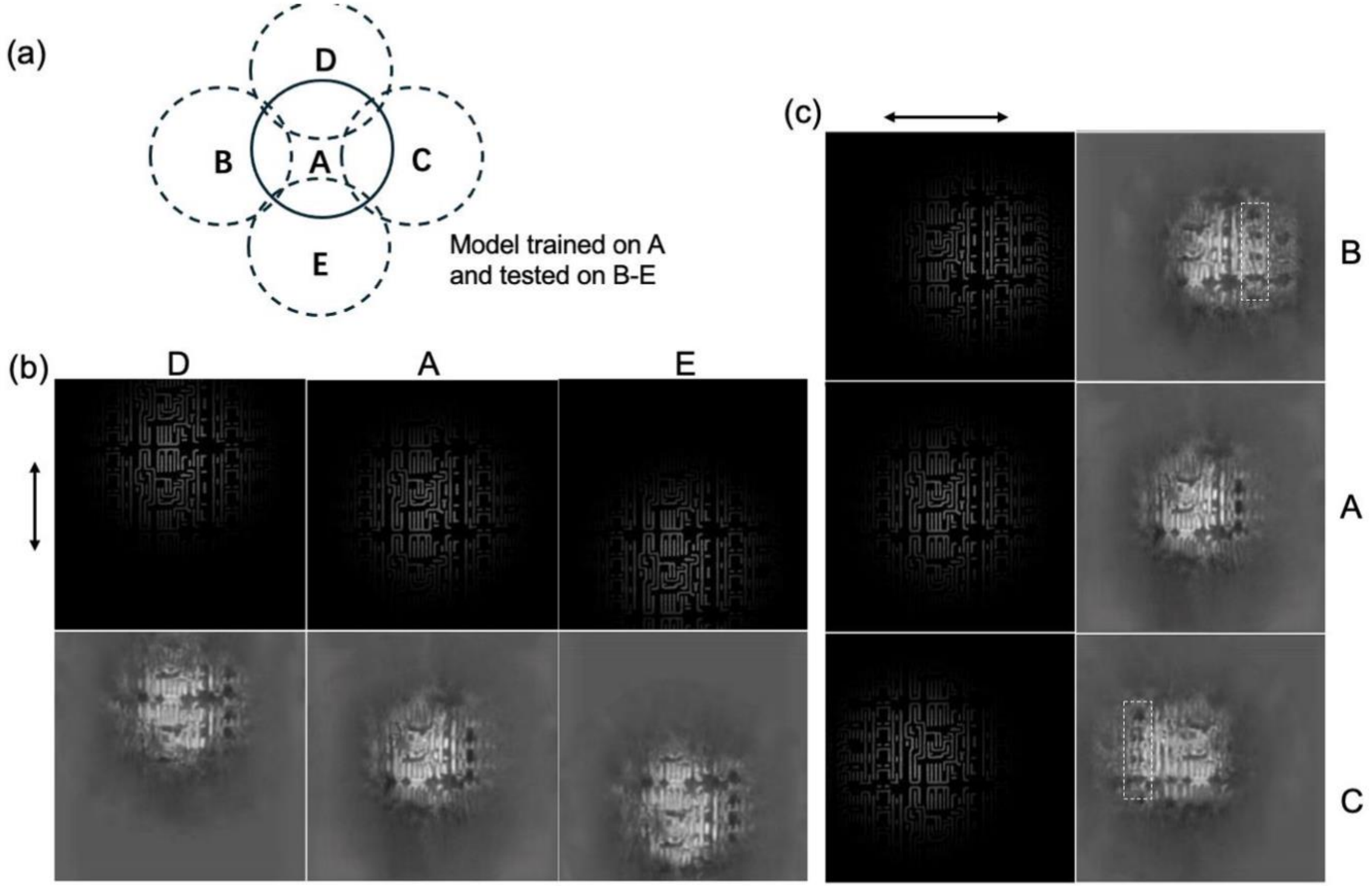
Optical


Workflow of SEM-to-Optical Image Translation
1 Data Collection
SEM
Optical (mSIL)
Sample
SEM image
Optical image
Acquire SEM and optical images of the same sample region
2 Data Preparation
SEM image
Vignetting mask
Pre-processed SEM
Optical image (target)
Prepare aligned SEM–optical training pair
3 Model Training / Testing
Input SEM
Input Optical
SinCUT / GAN model
Generator (G)
Discriminator (D)
Predicted optical image
Learn SEM → optical image translation
4 Model Evaluation
Predicted optical image
Original optical image
SSIM
SIFID
Line profile analysis
Evaluate similarity and image quality

Results



(a)
Optical (input)
Generated
SEM (ground truth)
(b)
SEM (input)
Generated
Optical (ground truth)



[Shape-Dependent, Deep-Learning-Assisted Metamaterial Solid Immersion Lens (mSIL) Super-Resolution Imaging](#)“, *arXiv*:2603.24371 (2026)

Conclusions

mSIL performance = shape + penetration + AI

- **Label-free super-resolution**
- **Best shape: super-hemispherical**
- **Penetration is key**
- **Virtual mSIL imaging**

Thank you!