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OEA founding issue cover technology achieves listing on the New York stock exchange

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Abstract: Conventional optical microscopy is fundamentally constrained by the optical diffraction limit (~200 nm), restricting the observation of nanoscale features in advanced manufacturing. To address this challenge, a remote-mode microsphere-enabled nanoscale imaging technology has been developed and successfully translated from laboratory innovation to industrial application. By utilizing a suspended transparent microsphere as a miniature lens, the system enables real-time, non-contact optical imaging and resolves 23 nm gaps on silicon wafers and 77 nm metal probes in hard-disk magnetic heads through reverse optical-path reconstruction of virtual images. The technology has been commercialized by PHAOS Technology, achieving over 300% annual sales growth and receiving the "Manufacturing Technology Disruptor of the Year" award. By integrating a universal lens adapter, the system allows a standard 20× objective to achieve imaging performance comparable to a 50× objective at only one-tenth of the cost of high-end super-resolution systems. This approach represents an important advancement in scalable and cost-effective nanometrology, providing a practical solution for real-time semiconductor inspection and industrial quality control.

Keywords: optical microscopy; nano-imaging; label-free; optical diffraction limit

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As a fundamental characterization tool across fields, such as biomedicine, semiconductor manufacturing, and food science, the optical microscope plays an indispensable role in scientific research and industrial production. Its advantages, including flexibility, portability, low cost, and rapid imaging, have enabled applications ranging from clinical disease diagnosis and real-time food quality monitoring to the precise inspection of semiconductor defects[1–6]. However, constrained by the optical diffraction limit, the resolution of conventional optical microscopes typically remains at around 200 nm, making it difficult to observe critical micro- and nanoscale structures, such as virus particles, nanoscale defects in integrated circuits, and biological macromolecules. This limitation significantly restricts its use in cutting-edge applications[7].

To overcome this bottleneck, researchers have developed advanced high-resolution imaging techniques, including transmission electron microscopy (TEM) and scanning electron microscopy (SEM), which require vacuum conditions, as well as specialized methods, such as atomic force microscopy (AFM) and fluorescence super-resolution microscopy[8–10]. Yet these approaches face practical challenges: electron microscopy requires complex sample preparation and is unsuitable for imaging living samples, while AFM and fluorescence-based methods are limited by near-surface sensitivity or labeling requirements. Consequently, achieving label-free, real-time, and non-contact imaging with nanoscale resolution, while preserving the advantages of traditional optical microscopy, has become an urgent challenge and a key direction for next-generation microscopy development.

Addressing this challenge, the research team led by

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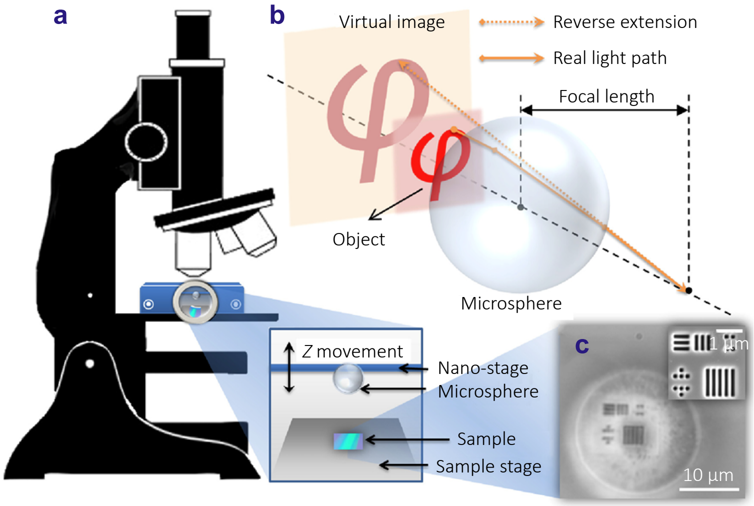

Fig. 1 | (a) Schematic diagram of the remote-mode optical microsphere setup. (b) Mechanism to illustrate the enlarged virtual image by the microsphere. (c) Optical image captured by this system (sample: semiconductor testing sample; scale bar: 10 µm; imaged by a 20 µm silica microsphere compiled to an oil-immersion optical microscope with a 100× objective lens, *NA*=1.4). Inset: SEM image (scale bar: 1 µm). Figure reproduced from ref.[11], under a Creative Commons Attribution License.

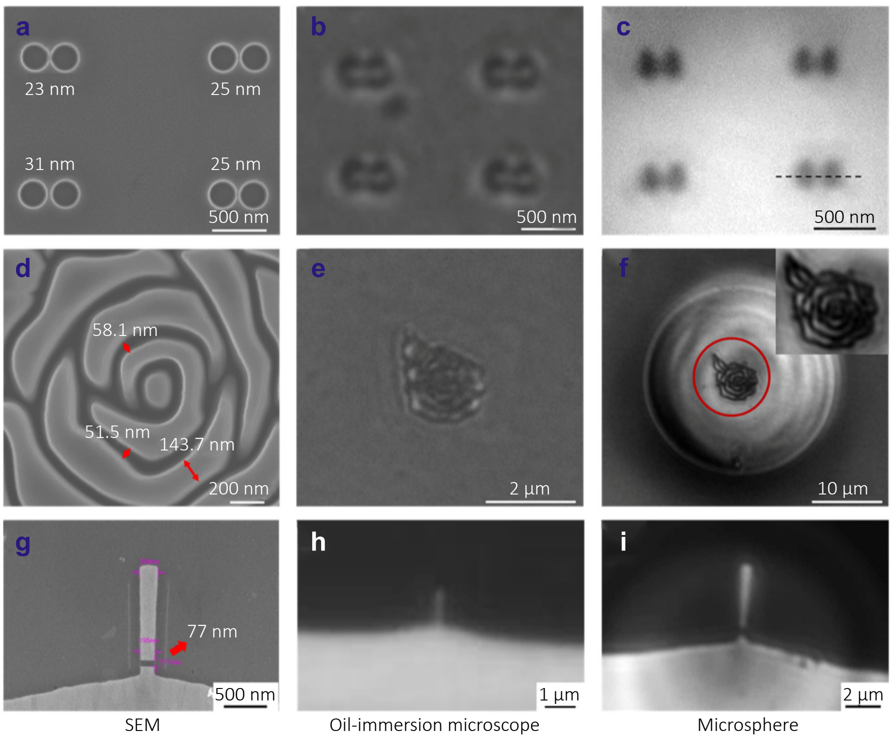

Fig. 2 | (a–c) Imaging of nano-dot pairs with nano-gap on a Si wafer. (a) SEM image of the samples, showing sizes of nano-gaps in between each pair of nano-dots. (b) Imaging of the samples by an oil-immersion microscope (neighboring nano-dots cannot be resolved clearly). (c) Neighboring separated nano-dots are resolved clearly by a microsphere with 20 µm diameter. The back dash line in (c) indicates the line cut. (d–f) Imaging of samples with complex features (the "nano-rose"). (d) Zoomed-in SEM image with size notations, it shows that the typical line width of the structure is ~140 nm, and separated by nano-grooves with a typical size ranging from 50–60 nm. (e) Imaging result by the oil-immersion optical microscope. (f) Image under the 27 µm microsphere. The diameter of the microsphere is larger in order to contain the entire nano-rose in the central region (compared to the microsphere used for the imaging of nano-dots, the microsphere with a larger diameter is chosen to ensure the entire nano-rose pattern is in the central region of the microsphere. Inset: zoomed-in image under the microsphere). (g–i) Imaging of a magnetic head in a hard disc drive from the production line. (g) SEM image of the magnetic head, with a nano-gap of 77 nm. (h) Imaging by a conventional oil-immersion microscope. (i) Imaging by the microsphere nanoscope in non-contact mode. The three columns represent images obtained by SEM, oil-immersion optical microscope (100×, NA 1.4), and microsphere nanoscope, respectively. Figure reproduced from ref.[11], under a Creative Commons Attribution License.

Professor Hong MH from the Xiamen University, and previously at the National University of Singapore, has proposed a remote-mode microsphere-enabled nanoscale imaging technology[11]. The team designed an integrated optical control system (Fig. 1(a)), the core of which is a transparent microsphere suspended above the sample surface to function as a miniature lens. A magnified virtual image is formed through light refraction at the microsphere surfaces and is then captured by the objective lens of a conventional microscope[12–14]. The position and magnification of the virtual image can be precisely determined through reverse optical-path reconstruction (Fig. 1(b)). In practical imaging experiments, an oil-immersion microscope (100× objective, NA = 1.4) equipped with a 20 μm silica microsphere can clearly resolve the micro-features of semiconductor test samples, producing results highly consistent with SEM images (Fig. 1(c)).

In validating the core performance of the system, the team developed a universal lens adapter (Fig. 2(a)) that integrates a 400 μm microsphere with a conventional 20× objective lens, resulting in a significant improvement in imaging capability. Experiments on onion epidermal cells showed that the adapter enables a 20× objective lens to achieve imaging performance comparable to that of a 50× objective, while image-stitching techniques expand the field of view to 125 μm × 125 μm. The integrated device features a compact design and excellent mechanical stability. Further comparative studies confirm that a 20× objective equipped with the microsphere delivers accuracy comparable to a commercial 50× objective, requiring only minimal modification of existing equipment and substantially reducing the cost barrier for super-resolution imaging.

In resolution testing, the system demonstrated outstanding nanoscale performance. For a nanodot array containing 23–31 nm gaps on a silicon wafer (Fig. 2(a)), a traditional oil-immersion microscope failed to resolve adjacent nanodots (Fig. 2(b)). In contrast, a 20 μm microsphere clearly resolved the smallest 23 nm gap (Fig. 2(c)). Similarly, for the complex "nano-rose" structure featuring 50–60 nm grooves (Fig. 2(d)), imaging with a traditional microscope yielded blurred results (Fig. 2(e)), whereas a 27 μm microsphere provided clear visualization of the nanoscale textures (Fig. 2(f)). Importantly, for the 77 nm metal probe gap in hard-disk magnetic heads on production lines (Fig. 2(g)), the system achieved clear, real-time, non-contact imaging (Fig. 2(i)), a task beyond the capabilities of conventional oil-immersion microscopes (Fig. 2(h)).

This groundbreaking remote-mode microsphere nanoscale imaging technology has also achieved successful commercialization through PHAOS Technology. Its strong performance and practical applicability have enabled the technology to rapidly establish its presence in the industry, earning multiple prestigious honors. It was named "Manufacturing Technology Disruptor of the Year" at the Don't Panic Events Global Business Technology Awards and received the "Manufacturing Technology Excellence Award" at the 2024 Singapore Business Review National Business Awards. The technology's innovative approach, effective academia-industry collaboration model, and outstanding market adoption have garnered recognition from both industry professionals and evaluation bodies.

Commercialization of this technology has delivered remarkable market results. As early as 2022, annual sales of microscopy equipment incorporating this technology increased by more than 300%, making it one of the fastest-growing product lines in the field of optical microscopy. In terms of equipment compatibility, the commercial microsphere lens adapter can directly upgrade conventional optical microscopes. With only simple retrofitting, the imaging performance of a standard 20× objective lens can be elevated to a level equivalent to that of a 50× objective, at only one-tenth of the cost of purchasing a high-end super-resolution microscope—significantly lowering the investment threshold for research institutions and industrial users.

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