Direct laser writing of polymer nanowire waveguides for single-photon extraction from epitaxial quantum dots

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Direct laser writing (DLW) is a popular fabrication technique for miniaturizing optical systems[1]. In many instances, DLW provides interfaces between high-index materials that house integrated photonic devices and the outside world. In particular, the use of DLW for the collection of single photons from epitaxial quantum dots (QD) embedded within a layer of GaAs has recently garnered scientific attention for its ability to fiber-couple these sources[2]. However, the quality of the lithography beam used in DLW can deteriorate when it interfaces with materials of varying reflectivity or absorption. For example, when printing on the surface of a high refractive-index material, strong reflections cause a local increase in the effective laser intensity as well as standing wave patterns. Such effects are of particular concern as the DLW-printed structure size reaches the wavelength-scale. In this work, we overcome the issues associated with DLW on high-index material to fabricate 800 nm-diameter polymer nanowire waveguides for the collection of single photons from epitaxial InAs/GaAs QDs.

Typically, DLW is used to enhance the collection of such QDs by fabricating a lens system that shapes the far-field emission of a QD into optical modes more compatible with optical fibers[2]. As an alternative, we propose the fabrication of a cylindrical waveguide directly on top of the QD material, using waveguiding effects to funnel the near-field QD emission into an optical mode suitable for fiber coupling (Fig. 1). Collecting the near-field emission permits greater control over the expansion and guidance of the optical mode, and it can be incorporated with other photonic devices to further improve extraction. The challenge with this approach is that the optimal waveguide diameter can be much smaller than that of a lens. For our system, the optimal nanowire (cylinder) diameter is 800 nm while that for a lens would be approximately 20 μm. This order-of-magnitude difference in the critical dimension magnifies the effects of reflections near the surface of the substrate, leading to sidewall corrugations and greatly reduced yield as shown in Fig. 2a. To reduce corrugations and improve yield, we employ two techniques: (1) angle-mounting the sample so that back-reflected lithography light is not parallel to the incident light, and (2) a previously reported advanced development method[3] incorporating a flood exposure step. Electromagnetic simulation (Fig. 1(b)) of these improved geometries indicates that the remaining corrugations will have a limited influence on nanowire performance. Fabricated nanowire waveguides on QD-containing substrates are currently being tested, and measurement results will also be presented.

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[1] P.-I. Dietrich, et al., "In situ 3D nanoprinting of free-form coupling elements for hybrid photonic integration," *Nature Photonics* **12**, 241–247 (2018).
[2] L. Bremer, et al., "Quantum dot single-photon emission coupled into single-mode fibers with 3D printed micro-objectives," *APL Photonics* **5**, 106101 (AIP, 2020).
[3] J. Purtov, et al., "Improved development procedure to enhance the stability of microstructures created by two-photon polymerization," *Microelectronic Engineering* **194**, 45–50 (2018).

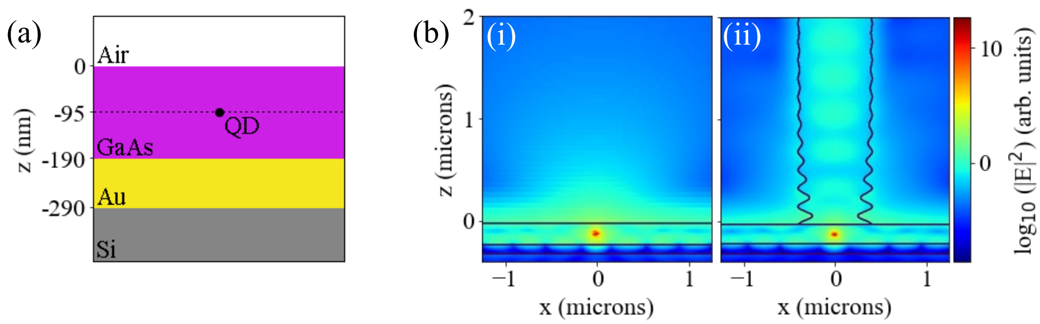

Figure 1: Nanowire waveguide for single-photon collection: The layer stack for our QD source (a) utilizes an Au back reflector to increase emission in the positive z direction. In comparison to the layer stack alone (b, i), the emission of a polymer nanowire (b, ii) better controls the QD emission, even when that nanowire has small corrugations near the base. With an 800 nm diameter and 160 nm corrugations at the base, the QD is expected to radiate over 90% of its power into the fundamental nanowire waveguide mode with an overall system efficiency of 5%, roughly a factor of 5 enhancement relative to the maximum possible free-space collection for the system without a nanowire.

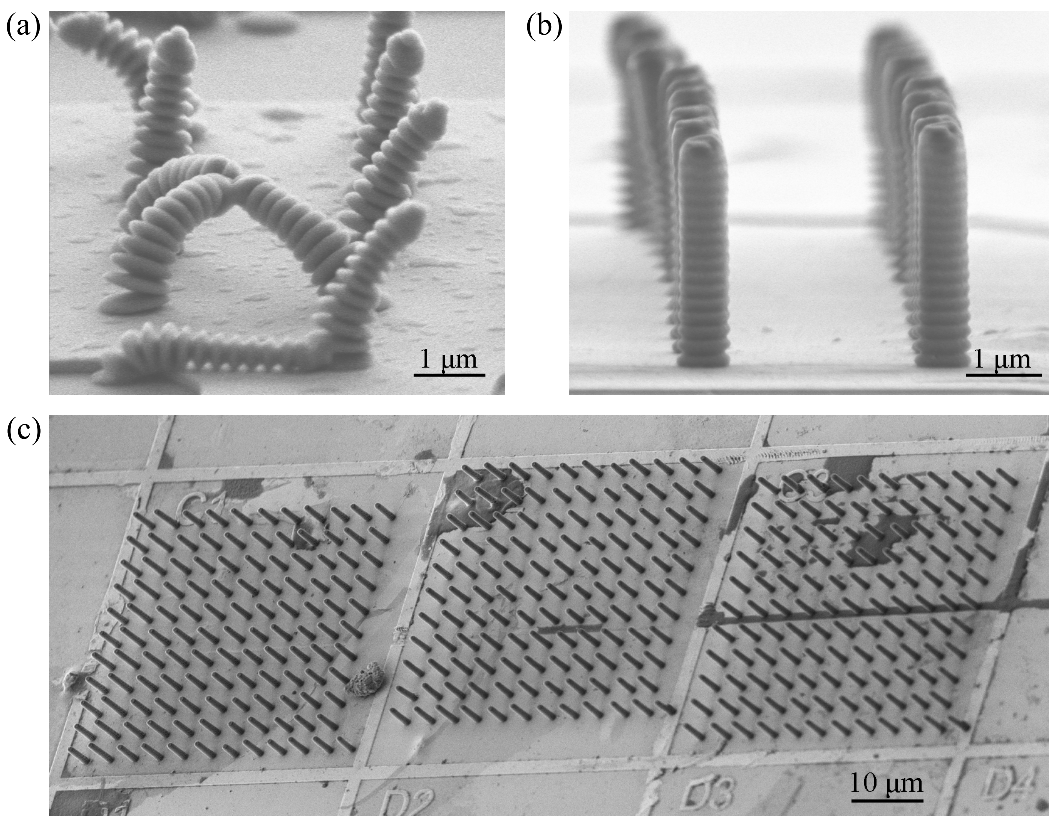

Figure 2: Corrugation reduction in DLW nanowire fabrication: When the lithography beam is perpendicular to a highly reflective printing surface, reflections and standing waves will cause corrugated sidewalls (a), but angle-mounting the substrate and using UV flood exposures reduces corrugation depths to less than 200nm (b), resulting in high yield nanowire fabrication (c).