On target – accurate integration of quantum dots and bullseye cavities

Craig R. Copeland,[1] Adam L. Pintar,[1] Ronald G. Dixson,[1] Ashish Chanana,[1] Kartik Srinivasan,[1,2] Daron A. Westly,[1] B. Robert Ilic,[1] Marcelo I. Davanco,[1] and Samuel M. Stavis[1]*

[1]*National Institute of Standards and Technology (NIST), Gaithersburg, Maryland 20899,*
[2]*Joint Quantum Institute, NIST/University of Maryland, College Park, Maryland 20742,*
[*]*samuel.stavis@nist.gov*

Self-assembled quantum dots are promising light sources for quantum networks and sensors. These emerging technologies require the accurate integration of quantum dots and photonic structures, but epitaxial growth forms quantum dots at random positions in semiconductor substrates. Optical localization of these random positions can guide the placement of photonic structures by electron-beam lithography.[1] This integration process requires the reliable registration of position data across microscopy and lithography systems. However, large errors can result from multiple sources, including lithographic and cryogenic variation of reference dimensions for microscope calibration, as well as localization errors from optical distortion. Such errors tend to increase across an imaging field, presenting a critical impediment to exploiting the throughput and scalability of widefield microscopy. In this study, we target this problem and show how our solution enables accurate integration to improve device performance and process yield.

We develop our methods of traceable localization[2] to calibrate a cryogenic localization microscope – an optical microscope with the sample and objective lens inside of a cryostat, and custom optics outside of the cryostat. We fabricate and characterize arrays of submicrometer pillars in silicon (100) (Figure 1a), creating microscopy standards with both traceable reference positions and traceable reference data for thermal expansion coefficient.[3] We image these arrays with the cryogenic microscope at approximately 1.8 K, localize the pillar positions, and use the reference data to calibrate the microscope. Our calibration determines the scale factor of the imaging system and corrects position errors due to complex distortion, among other aberration effects (Figure 1b-c).

We combine the results of this cryogenic calibration with our previous assessment of fabrication accuracy by electron-beam lithography,[2] introducing a comprehensive model of the effects of registration errors on Purcell factor. This performance metric quantifies the radiative enhancement that occurs upon integration of a quantum dot into a bullseye cavity (Figure 1d). For an exemplary system,[1] the Purcell factor reaches a maximum value of approximately 11 for error-free registration of the quantum dot and cavity center. Our model demonstrates the possibility of greatly improving Purcell factor across a wide field (Figure 1e-f). Depending on the Purcell factor threshold, on-target integration can increase yield by one to two orders of magnitude (Figure 1g). This foundation of accuracy will enable a transition from demonstration devices to efficient processes, leading to the reliable production and statistical characterization of quantum information systems.

---

[1] L. Sapienza *et al*., *Nature Communications*, 6, 7833, 2015.
[2] C. R. Copeland, et al., *EIPBN*, 2021, *arXiv*, 2106.10221, 2021.
[3] T. Middelmann *et al*., *Physical Review B*, 92, 174113, 2015.

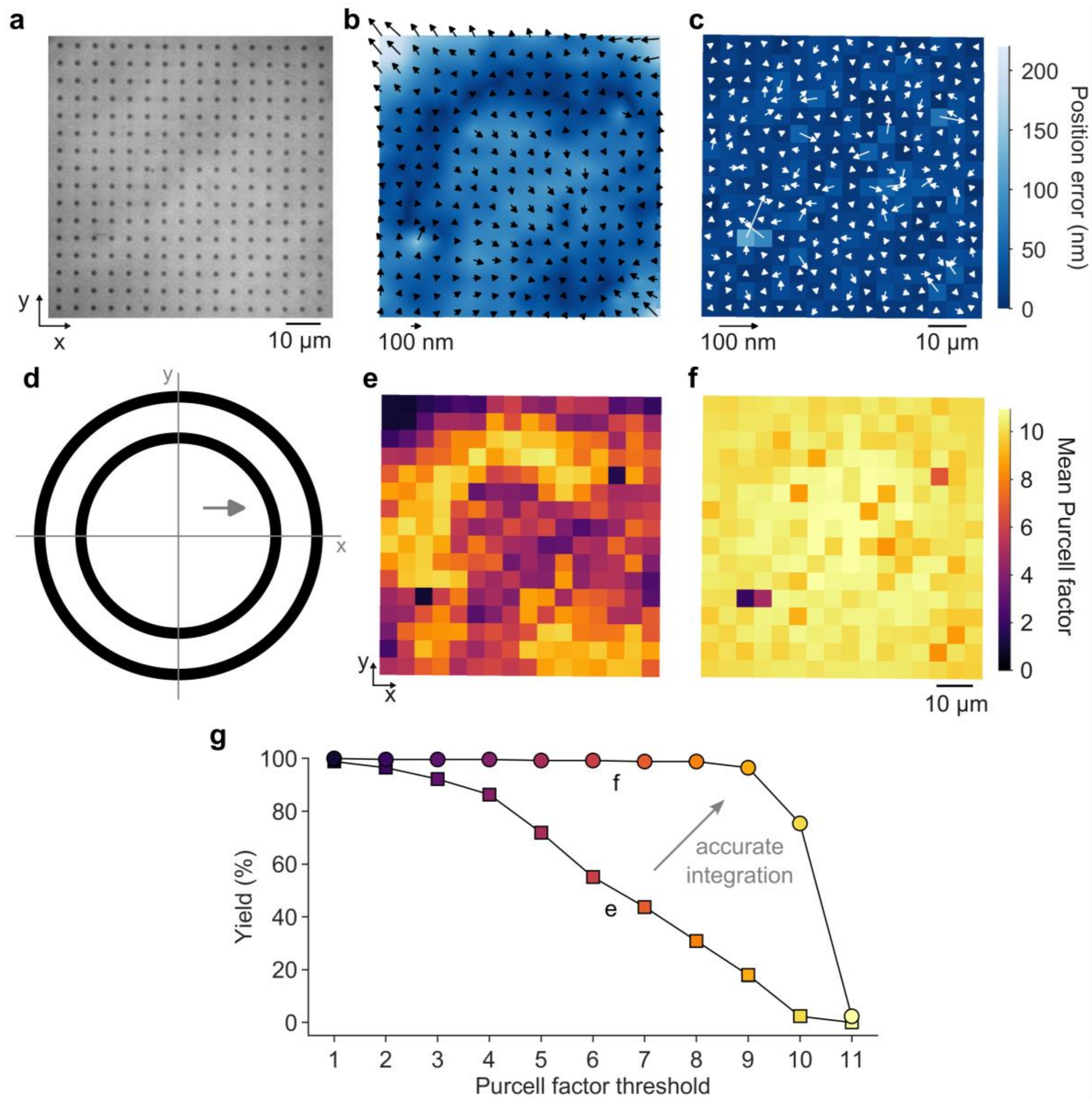

Figure 1. (**a**) Brightfield optical micrograph showing a representative array of silicon pillars with a traceable pitch of 5001.64 nm ± 0.54 nm at a temperature of approximately 293 K. This uncertainty is a 68 % coverage interval. (**b-c**) Vector plots and color maps showing position errors (b) before and (c) after correction of complex distortion effects at a temperature of approximately 1.8 K. Traceable reference data account for a net thermal contraction of approximately 1.1 nm. (**d**) Schematic showing a dipole emitter with an azimuthal angle of 0 inside the first two trenches of a bullseye target cavity. The offset from center indicates a registration error. (**e-f**) Plots showing mean Purcell factor across the imaging field for the dipole angle in (d), corresponding to (e) the state of the art[1] and including the position errors in (b), and (f) on-target integration and including the position errors in (c). (**g**) Plot showing theoretical yield as a function of Purcell factor threshold, which is the minimum value of Purcell factor that is necessary for a certain radiative enhancement, for (squares) the values in (e), and (circles) the values in (f). For an exemplary Purcell factor threshold of 10, the yield increases from 2 % to 75 %.