

Massive Parallel Positioning of Nanodiamonds on Nanophotonic Structures

Justus C. Ndukaife^{1,3}, Benjamin P. Isaacoff², Mikhail Y. Shalaginov¹, Simeon Bogdanov¹, Agbai George Agwu Nnanna³, Julie S. Biteen², Mordechai Segev⁴, Vladimir M. Shalaev¹, Alexandra Boltasseva¹

¹School of Electrical & Computer Engineering and Birck Nanotechnology Center, Purdue University, West Lafayette, IN 47907, USA

²Department of Chemistry, University of Michigan, Ann Arbor, Michigan 48109-1055, USA

³Water Institute, Purdue University Northwest, Hammond, IN 46323, USA

⁴Department of Physics, Technion, Israel Institute of Technology

*aeb@purdue.edu

Abstract: Precise and scalable positioning of nanoscale emitters, such as nanodiamonds with color centers, on solid substrates is essential for realizing integrated quantum devices and sensor arrays. We present a novel approach to meet this need.

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Nanophotonic devices, particularly plasmonic components, offer an unprecedented capability to significantly enhance the interaction between light and matter to enable the realization of miniaturized optical and optoelectronic devices [1]. In order to exploit the fundamental interactions of nanoscale quantum emitters and nanophotonic structures, advanced nanoassembly schemes are needed [2]. The conventional techniques such as AFM manipulation and multi-step nanofabrication are too slow to meet this need.

To address this challenge, we introduce a novel nanoassembly scheme termed Directed Spatially Selective Self Assembly (DS³ Assembly) and demonstrate precise placement of nanodiamonds with nitrogen-vacancy (NV) centers on plasmonic nanoantennas. The technique harnesses the photothermal heating of illuminated plasmonic nanoantennas and applied a.c. bias to induce a large scale electrothermoplasmonic flow [3,4] carrying a large number of suspended nanoparticles. Furthermore, the plasmonic nanoantennas induce a high gradient in the applied a.c. electric field around each nanoantenna, which in turn induces a local a.c. electro-osmotic flow [5] and dielectrophoretic (DEP) force around each nanoantenna. When the nanodiamonds carried in the electrothermoplasmonic flow intercepts the force field of the local a.c. electro-osmotic flow and DEP force, they are stripped from the flow streamlines and rapidly localized in the vicinity of the nanoantennas (see Fig. 1a). The nanodiamonds then become permanently fixed at the surface of the nanoantennas by van der Waals forces. In doing that, we harness three different fundamental effects for an exceedingly important engineering task: controlling the landscape and spatial distribution of nano-emitters and nano-sensors.

For the experimental demonstration, we employ gold nanodisks with a diameter of 200 nm and thickness of 120 nm (figure 1b). The nanoantennas are fabricated on a glass substrate with 100 nm gold film using electron beam lithography and lift-off. An ITO-coated glass coverslip is placed over the patterned substrate and separated with a dielectric spacer that is 90 μm thick, creating a microfluidic channel between the substrate and the coverslip. For the nanoassembly experiments, 100 nm diameter nanodiamonds containing NV ensembles are introduced into the microchannel formed between the substrates. A near-infrared laser beam (976 nm) is loosely focused to a 4 μm spot on the plasmonic nanoantennas. An a.c. electric field with an amplitude of 600,000 V/m and a frequency of 6 KHz is applied to the microchannel to initiate the assembly. After the laser and a.c. field are turned OFF, the nanodiamonds still remain immobilized on the nanoantennas, as depicted in figure 1c.

Our results represent a novel scheme for deterministic positioning of nanodiamonds on nanophotonic structures in a parallel manner. The technique presents fundamentally new possibilities for the fabrication of large sensor arrays capable of detecting temperature and electromagnetic fields on the nanoscale. In a similar vein, the technique offers a unique avenue for placing single-photon emitters at predesigned positions, and distances that enable quantum correlations between emission events. With this in mind, future experiments will also include the realization and characterization of plasmon-enhanced room temperature single photon sources, and plasmonic registers by assembling the nanodiamonds on slot waveguides. Furthermore, we will also explore the fabrication of metasurface devices for color printing via this directed assembly scheme.

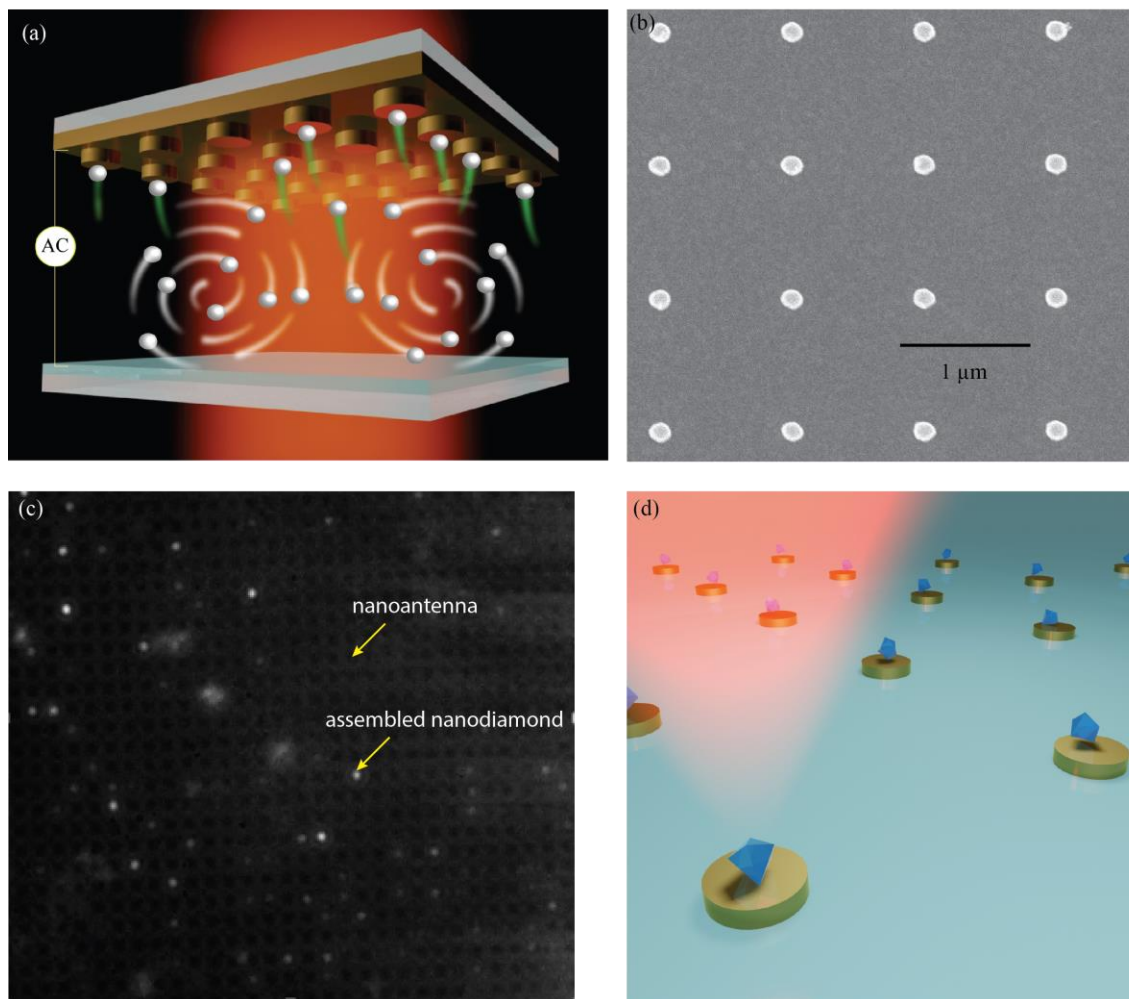


Figure 1: (a) Schematic of the platform for directed spatially selective self-assembly where plasmonic nanoantennas are illuminated and a low frequency ($<10\text{KHz}$) a.c. electric field is applied to assemble nanoparticles precisely on the nanoantennas. (b) SEM image of the plasmonic nanoantenna array. (c) Experimental optical image after the nanodiamonds have been assembled on the nanoantennas. After the laser and a.c. field is turned OFF, the nanodiamonds still remain immobilized on the nanoantennas. Note that the nanodiamonds are assembled precisely at the site of each nanoantenna. (d) Depiction of the nature of the assembly of the nanodiamonds on the nanoantennas as obtained in (c).

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