Plasmon Nano-Optical Tweezers for Integrated Particle Manipulation: A Route to Positioning, Sensing, and Additive Nanomanufacturing On-chip

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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. In order to exploit the fundamental interactions of nanoscale objects (such as quantum emitters and biomolecules) with nanophotonic structures, advanced nano-assembly schemes are needed. Plasmon nano-optical tweezers employ plasmonic nanoantennas to create highly localized and intensified electromagnetic fields, and are at the core of a very active research direction towards the efficient trapping of nanoscale objects, which cannot be addressed with conventional diffraction-limited optical tweezers. A long standing issue with previously proposed solutions is how to controllably load the plasmonic trap on-demand without relying on Brownian diffusion. This thesis presents novel designs for plasmon nano-optical tweezers. First, a new design paradigm known as the Hybrid Electrothermoplasmonic Nanotweezer (HENT) was developed to address the challenge of inability to rapidly and controllably load a plasmonic nanotweezer, an issue that has limited the performance of prior plasmonic nanotweezers. In HENT, the intrinsic localized heating of the illuminated plamsonic nanoantenna is harnessed in conjunction with an applied AC electric field to initiate rapid microscale fluid motion and particle transport with a velocity exceeding 10 µm/s, which is over two orders of magnitude higher than previously predicted in the literature. This microscale fluidic transport enables on-demand long-range rapid delivery of single nano-objects to addressable plasmonic hotspots where they can be trapped and "locked" in place. By applying a DC field, the trapped nano-objects can also be immobilized on the plasmonic hotspots thus enabling effective low-power nanomanufacturing on-chip.

The second component of this thesis solves the challenge of deterministic placement of nanoscale objects such as quantum emitters in a parallel manner on plasmonic nanoantennas to enhance light-matter interaction. The conventional techniques such as AFM manipula-tion 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 (DS^{3}

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 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 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. 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

Finally, this thesis also demonstrates a thermoplasmonic metasurface that allows combining directed self-assembly of nanoparticles with tunable inter-element spacing and single nanoparticle trapping resolution with high-throughput in one lab-on-a-chip platform. The excitation of localized and Bloch surface plasmon polariton waves upon illumination of the metasurface comprising of sub-wavelength nanoholes in a metal film create a unique optical and thermal landscape that governs the nature of the nanoparticle assembly. Self-limiting single nanoparticle resolution trapping is achieved in the region of the metasurface with a single nanohole, while directed self-assembly of a large ensemble of nanoparticles is achieved in the region with arrays of closely spaced plasmonic nanoholes. These trapping features occur in an inverted configuration against gravity, which was previously thought to be impossible. The novel layouts for plasmon-assisted optical trapping developed in this thesis open up a myriad of applications in single molecule analysis, quantum photonics, self-assembly and creates an auspicious platform for exploring non-equilibrium physics.