Additive Integration from Nanomaterials to Devices

by
Weikun (Spencer) Zhu

Nanomaterials, confined in one or more dimensions, exhibit unique properties that open new technological paradigms beyond their bulk counterparts. Realizing these potentials requires deterministic and scalable integration of these materials onto solid-state platforms, which is not readily feasible through conventional top-down strategies.

In this thesis, the gap between nanomaterials and functional devices is addressed through developing additive integration strategies with a particular focus on diverse nanocrystals. To this end, my thesis pursued two directions. The first relies on engineering nanoscale forces to direct placement of nanocrystals with individual particle control. Here, we developed nanoparticle contact printing, where particles are spatially arranged using capillary assembly and then transfer printed, in a completely dry and sacrificial layer-free approach, onto arbitrary surfaces with > 95% yield and < 50 nm spatial accuracy. Using this approach, emitter-integrated plasmonic cavities for enhanced light emission and reconfigurable mechanical nanoactuators were demonstrated.

Although robust and versatile, the directive forces reduce with smaller nanocrystal dimensions and are often insufficient in sub-10 nm regime. Instead of nanocrystal placement post synthesis, my thesis introduces an alternative approach where the nanocrystal is synthesized deterministically on-site for direct device integration. Using halide perovskites as an example, in one approach, we demonstrated such on-site growth by localizing the precursors using a topographical template with asymmetric surface wettability. Through this approach, we achieved < 50nm $CsPbBr_3$ nanocrystals deterministically formed with < 50nm placement accuracy. Leveraging this platform, arrays of nanoscale light-emitting diodes were demonstrated.

We further confined the on-site growth to the quantum regime by developing a scanning probe technique. Through this approach, perovskite nanocrystals can be patterned in arbitrary designs and composition, with resolution down to the single-emitter level. With this extreme resolution, we demonstrated room-temperature high-purity single-photon sources based on cesium lead iodide quantum dots, capable of on-demand integration with photonic structures.

In conclusion, the platforms developed in this thesis enable pristine integration of emerging nanocrystalline materials into functional devices, paving the way for new scientific frontiers and next-generation technologies in optoelectronics and photonic quantum applications.

Thesis Supervisor: Farnaz Niroui
Title: Associate Professor of Electrical Engineering and Computer Science