500 Word Abstract

Metallic Nano-Rings for Enhanced Extraction of Light from Single InAs/GaAs Quantum Dots

Bright and pure single-photon sources are an essential component of emerging quantum technologies and solid-state single-photon emitters are the most promising candidates for integration in on-chip devices [1]. However, such emitters can suffer from poor light extraction efficiencies, because of the large difference in refractive index between the bulk semiconductor and air, that results in only a small fraction (down to less than 1%) of the emitted photons reaching free-space collection optics, due to total internal reflection. In order to overcome this issue, photonic devices, such as micro-pillars, nanowires and suspended gratings have been developed [1]. Such devices show extraction efficiencies reaching up to about 70% but present narrow operation bandwidths and require relative tuning of the emitter/cavity emission wavelengths to achieve resonance conditions. Solid-immersion lenses deposited onto the sample surface, instead, allow broadband light collection by focussing the excitation and the emitted light: however, modest enhancements of up to a factor 10 are obtained if optimal lens-emitter alignment is achieved [2].

We present a new device, based on a metallic nano-ring placed on the sample surface and centred around a specific emitter that allows a broadband lensing effect that improves the amount of light channeled towards the collection optics of up to a factor 25 [3].

Our sample contains a low density of InAs quantum dots (QDs) grown by molecular beam epitaxy and capped by 95nm of GaAs. A micro-photoluminescence imaging set up is used to locate single QDs with nanometer accuracy [4] and finite-difference time-domain simulations are performed to optimize the metallic ring dimensions and maximize the QD vertical extraction of light.

Individual QDs are located with respect to alignment marks and their emission properties are analysed by means of micro-photoluminescence spectroscopy, under 785nm continuous-wave laser excitation. Metallic rings are then deposited on the sample surface, centred around the single emitters location, by means of aligned electron-beam lithography, Cr(7nm)/Au(60nm) thermal evaporation and chemical lift-off. After ring placement, we observe increases of up to ×25 on the emission intensity of selected QD emission lines.

The metallic nanorings that we have developed are broadband, since they are based on a lensing effect. They are relatively simple to fabricate and are compatible with any combination of emitter (of quantum or classical light) and substrate, including defect centres in diamond and 2-D materials, colloidal QDs and quantum well structures. Furthermore, the ring dimensions (inner radius of 220 nm) are compatible with photolithography and nano-imprint techniques, allowing for device scalability. The metallic rings can also be used as top contacts for applying local external electric fields, for wavelength/charge tuning of single QDs, whilst providing enhancement in the intensity of the emitted light collected into free space.

[1] O. Gazzano et al., *J. Opt. Soc. Am. B* **33**, C160 (2016)
[2] K. Serrels et al., *J. Nanophotonics* **2**, 021854 (2008)
[3] O. J. Trojak et al., *Appl. Phys. Lett.* **111**, 021109 (2017)
[4] L. Sapienza et al., *Nat. Commun.* **6**, 7833 (2015)

300 Word Summary

Metallic Nano-Rings for Enhanced Extraction of Light from Single InAs/GaAs Quantum Dots

Bright and pure single-photon sources are an essential component of emerging quantum technologies [1]. Solid-state single-photon emitters have a number of desirable attributes, which make them attractive candidates for on-chip devices [2]. However, such emitters can suffer from poor extraction efficiencies, because of the large difference in refractive index between the bulk semiconductor and air that results in only a small fraction (down to <1%) of emitted photons reaching free-space collection optics. To improve the light extraction efficiency, different photonic geometries have been developed (like micropillars, nanowires, circular gratings): however these require complex fabrication and/or provide narrow operation bandwidths.
We present a new device, based on a metallic nano-ring that provides a broadband lensing effect that increases the amount of light emitted into free space [3].

A micro-photoluminescence imaging set-up was used to locate single QDs with nanometer accuracy [4], metallic rings are then deposited on the substrate surface, centred around single emitters. We show that the metallic rings allow an increase of up to ×25 on the emission intensity of selected QD emission lines.

The metallic nanorings that we have developed are broadband, since they are based on a lensing effect. They are relatively simple to fabricate and are compatible with any combination of emitter (of quantum or classical light) and substrate. Furthermore, the ring dimensions (inner radius of 220 nm) are compatible with photolithography and nano-imprint techniques, allowing for device scalability. Additionally the metallic rings can be used as top contacts for applying local external electric fields, for wavelength/charge tuning of single QDs.

[1] I. Aharonovich et al., *Nat. Photon.* **10**, 631 (2016)
[2] O. Gazzano et al., *J. Opt. Soc. Am. B* **33**, C160 (2016)
[3] O. J. Trojak et al., *Appl. Phys. Lett.* **111**, 021109 (2017)
[4] L. Sapienza et al., *Nat. Commun.* **6**, 7833 (2015)