In-situ electron-beam lithography for deterministic nanophotonic structures using low-temperature cathodoluminescence spectroscopy

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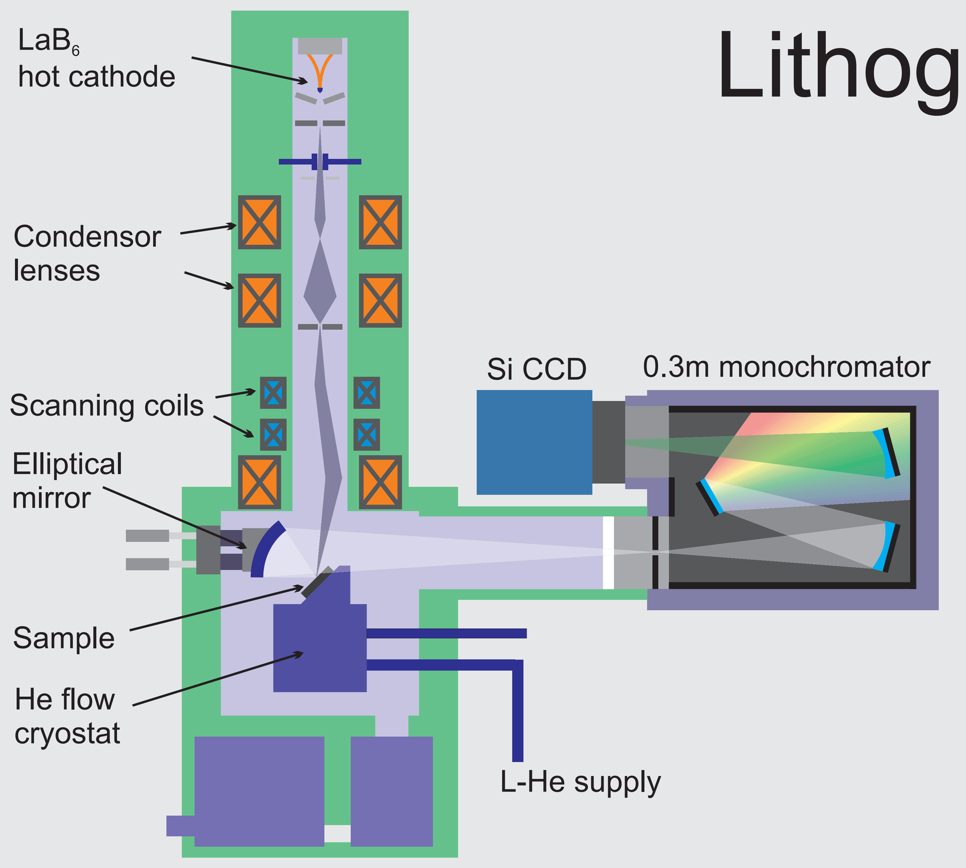
Motivation

- ♦ Development of deterministic non-classical light sources for optical quantum information technology.
- ♦ Necessity of controlling the spatial and spectral coupling between a QD and the optical mode of a microcavity.
- ♦ Previous attempts use site-controlled QDs to achive spatial alignment, but suffer from reduced optical quality and random spectral matching [1].
- ♦ Fabrication of deterministic quantum devices by optical in-situ lithography limits the minimum feature sizes to about 1 µm [2].
- ➔ Application of cathodoluminescence (CL) spectroscopy to identify QDs with suitable optical properties and to define nanophotonic structures by in-situ electron beam lithography [3].

Cathodoluminescence Lithography Setup



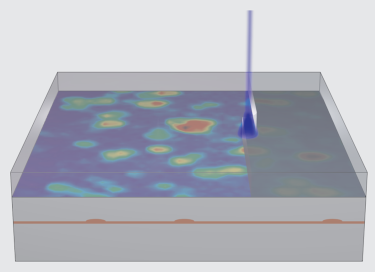
SEM:
- Acceleration voltage: 2 - 40 kV
- Beam current: 0 - 100 nA
- Custom-made EBL attachement

Spectrometer:
- 0.3 m McPherson monochromator
- Spectral resolution: 140 µeV at 1.2 eV

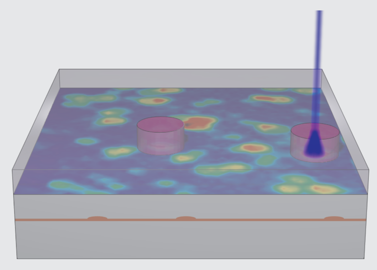
Integrated He-flow cryostat:
- Low vibration
- High mechanical stability
- Temperature range: 5 - 300 K

Technology

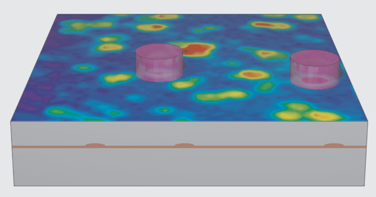
1. Sample preparation:
Spin coating of sample with 200 nm of high-resolution resist PMMA



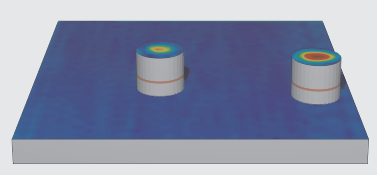
2. CL-mapping:
Low-temperature CL-mapping to select single QDs with suitable optical properties. The positive resist becomes completely exposed and soluble in the scanning area.



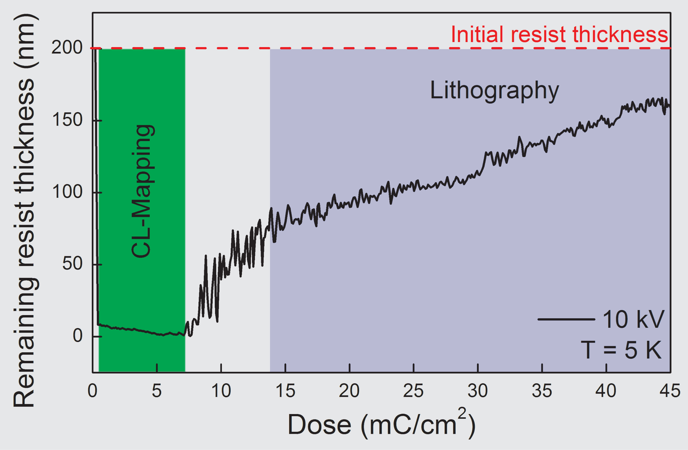
3. In-situ lithography:
A 2D fit algorithm determines the exact positions of the QDs. The electron beam is then used to define sub-µm mesa structures by a local inversion of the resist.



4. Resist development:
The developer which is selective on the non-inverted regions removes the soluble resist in the scanning area. The inverted PMMA remains on top of the sample.

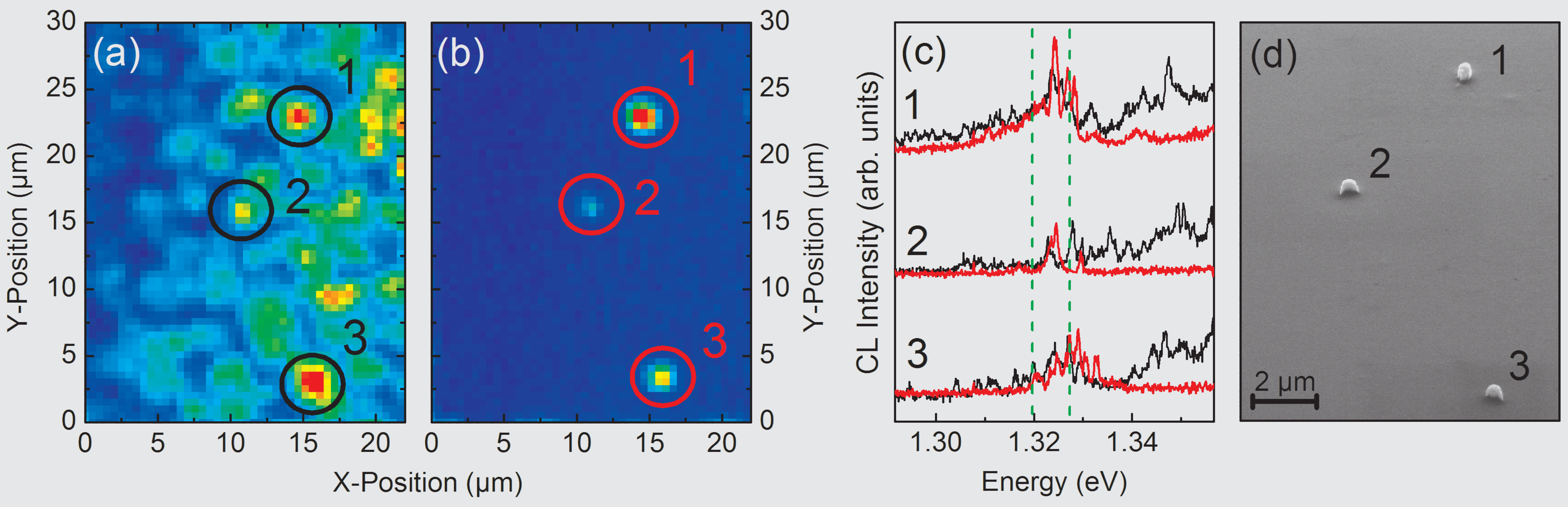


5. Etching
The remaining resist now acts as etching mask for the subsequent etching step using an ICP-RIE plasma ($BCl_2 + Cl_2 + Ar$) etcher.



Resist characteristics
The e-beam resist with an initial thickness of 200 nm becomes completely soluble during the initial CL-mapping process (up to 8 mC/cm², green) and electron-beam writing is done at larger doses (up to 45 mC/cm², blue) to invert the resist.

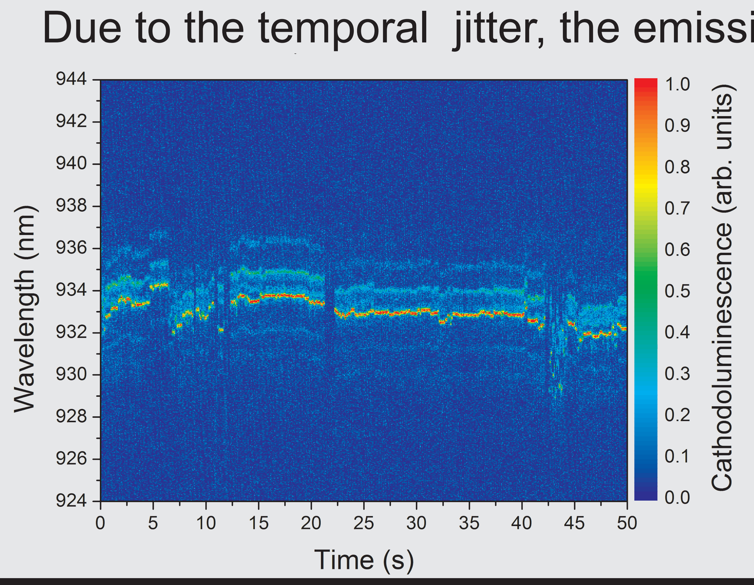
Fabrication



(a) CL-intensity map of a 22x30 µm² unprocessed area of the sample. The positions and spectral features of individual QDs can be extracted. The QDs labeled 1-3 are selected for mesa processing.
(b) CL-intensity map of the same area after sample processing. The only active regions remaining include the previously selected QDs.
(c) CL spectra of the three selected QDs before (black lines) and after (red lines) fabrication of the mesa structures. The dashed green lines indicate the spectral region used for a 2D-fitting algorithm.
(d) SEM image of the etched mesa structures with a diameter of 450nm.

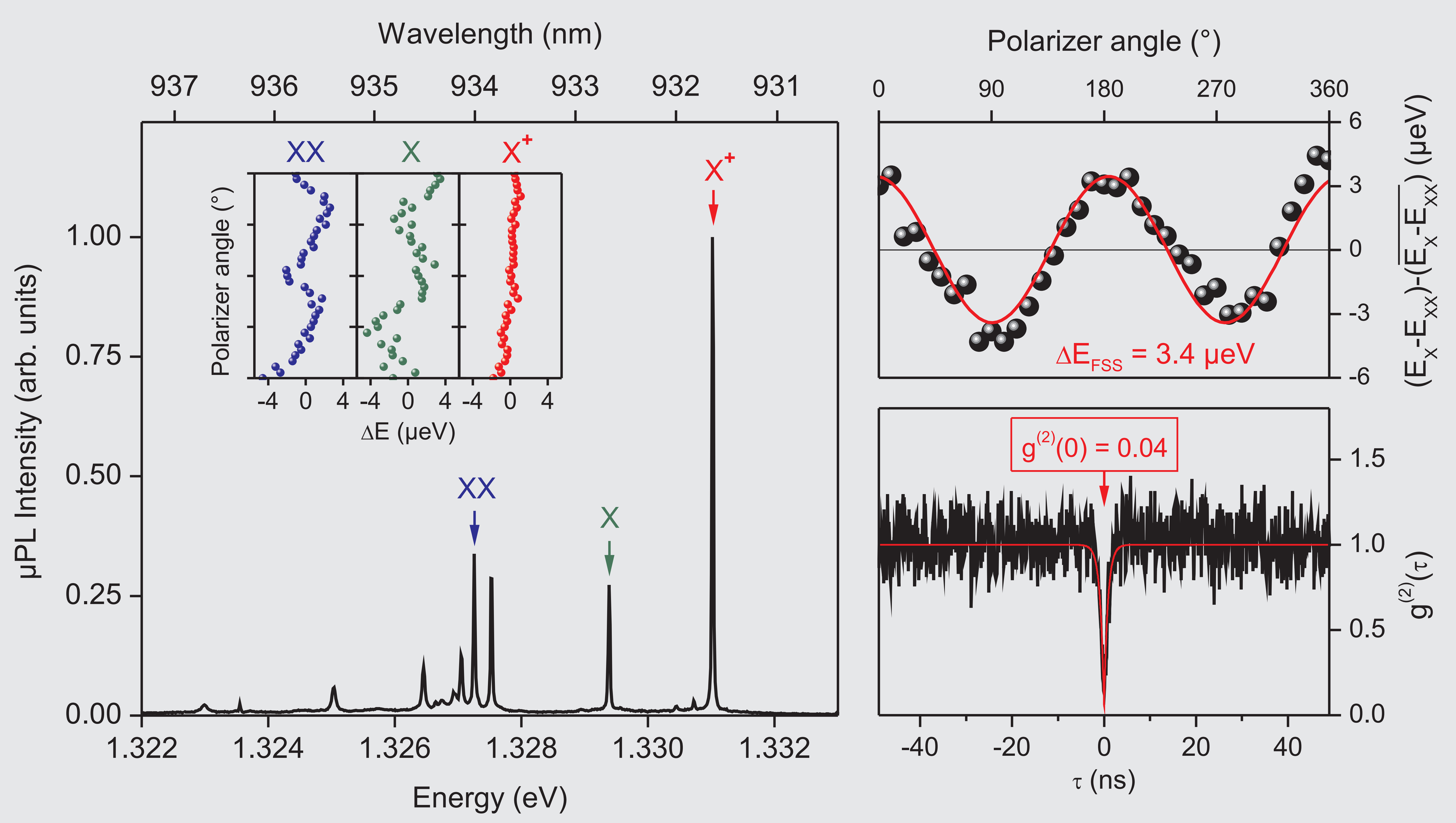
Identification of Single-QD Spectra

Due to the temporal jitter, the emission lines can be assigned to individual QDs.



Random charging and discharging of local defects
⇓
Variation of electrical field
⇓
Shifting of emission energies due to the Quantum Confined Stark Effect
⇓
Individual jitter pattern for each QD [4]

Optical Properties



Microphotoluminescence measurements indicate resolution-limited excitonic linewidths as small as 9 µeV and $g^{(2)}(0)$- values close to zero.

Summary

- ♦ Demonstration of a novel technology platform for deterministic quantum devices based on a combination of cathodoluminescence mapping and in-situ electron-beam lithography.
- ♦ Pre-selection of quantum emitters depending on their spatial and spectral properties paves the way for fully-deterministic photonic quantum devices.
- ♦ Fabrication of 450 nm sized mesa-structures, each containing a single QD with resolution-limited excitonic linewidths as low as 9 µeV and $g^{(2)}(0) = 0.04$.

References:

[1] C. Schneider et al., PSS A, **209**, 2379 (2012)
[2] A. Dousse et al., PRL, **101**, 267404 (2008)
[3] M. Gschrey et al., APL, **102**, 251113 (2013)
[4] S. Rodt et al., Phys. Rev. B **71**, 155325 (2005)

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