CMOS-Integrated Room-Temperature Quantum Sensing

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1. Introduction

Quantum sensors based on nitrogen vacancy (NV) centers in diamond offer unprecedented magnetic-field sensitivity at room temperature[1], enabling applications from industrial automation and biomedical diagnostics to civil and defense sensing. Current systems depend on bulky external lasers, microwave sources and optics, limiting portability and scalability. CMOS technology is attractive for the miniaturization of quantum sensors, as it can co-integrate circuits and optical sensing elements together in one solid-state device.

Challenge: Currently there exists no solution for the miniaturization of the light source for the optical excitation of color centers down to the µm-range to integrate complete quantum sensing systems into CMOS chips. OLED-on-silicon technology, known from microdisplays and matured to technological readiness in this context, seems to offer a promising solution to this problem.

Goal: Fully integrated quantum sensing system based on NV technology including:

- Optical excitation
- Microwave excitation (MW) including generation
- Optical detection
- Control circuitry
- Read-out circuitry

2. CMOS-Integrated Optical Quantum Sensing Platform

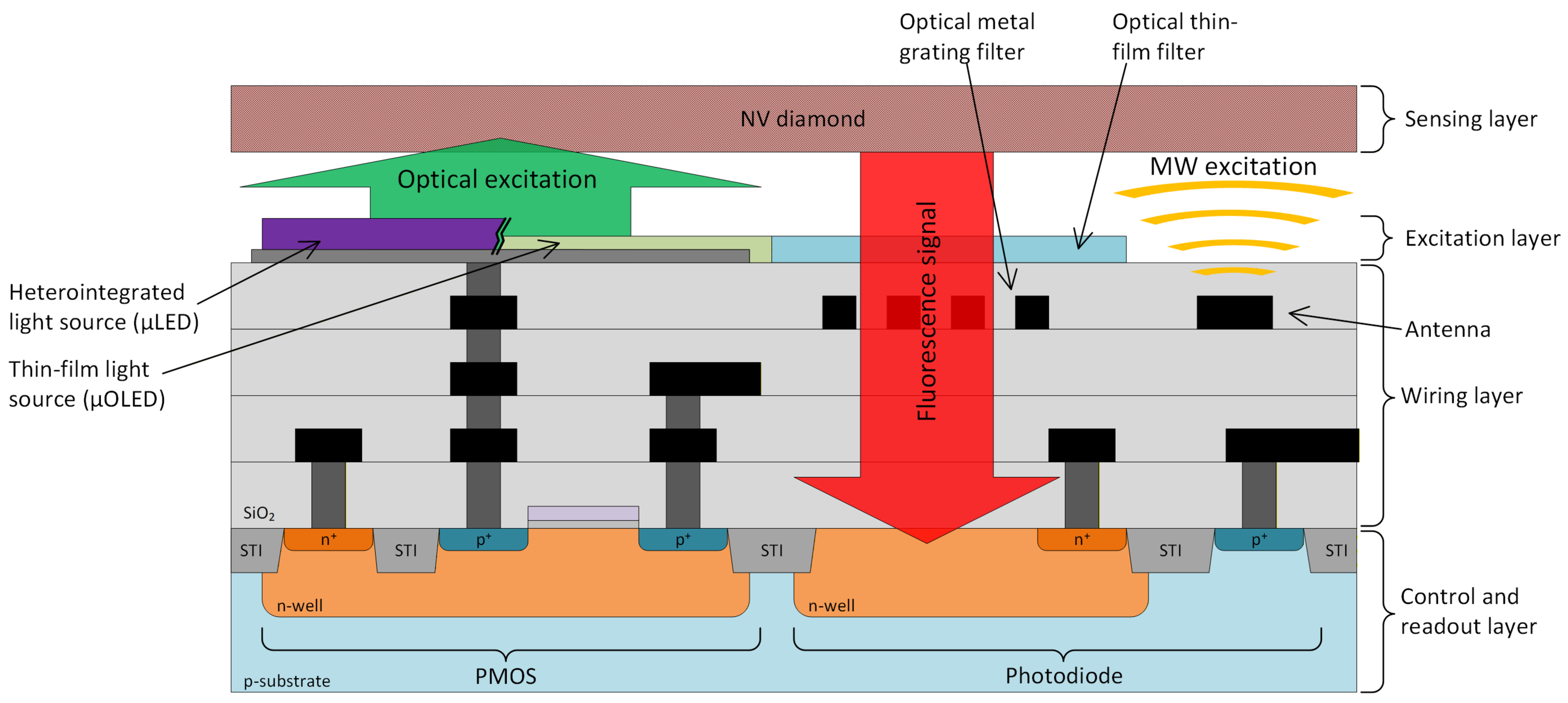

Figure 1. Schematic cross-section of the proposed CMOS-integrated optical quantum sensing platform.

The proposed concept subdivides the system in multiple functional layers – sensing layer, excitation layer, wiring layer and the control and read-out layer. It integrates all optical and electronic functions in a multilayer stack. NV centers in diamond form the sensing layer, while an OLED-on-silicon excitation layer provides on-chip optical excitation and supports thin-film filters for spectral selectivity. The CMOS back-end interconnects excitation, detection, and readout circuitry and can host the MW antenna and additional optical grating filters. By depositing OLEDs above circuitry and wiring areas that cannot be used for detection, the chip operates in a bidirectional mode, greatly increasing fill factor and enabling a fully integrated quantum sensor systems on a single CMOS chip. The design allows for diverse antenna geometries, sub-pixeling strategies and on-chip data processing, making the platform suitable for both single sensor and array configurations.

3. Proof-of-Concept Experiments

To demonstrate the capability of OLED-on-silicon technology in conjunction with CMOS in the context of quantum sensing, several proof-of-concept experiments were conducted[2].

CMOS Detector Test

- Evaluation of the sensitivity of an integrated camera in a bidirectional microdisplay technology[3]
- NV fluorescence clearly visible when comparing pictures without and with NV diamond

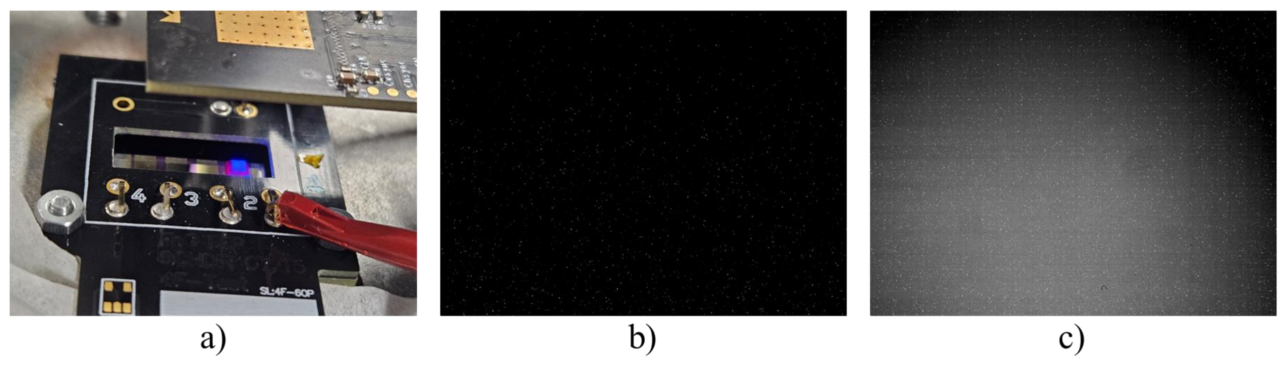

Figure 2. a) Measurement setup of bidirectional microdisplay above OLED test chip with NV diamond, a long-pass filter was inserted in between. b) Picture taken with the long-pass filter but without the NV diamond. c) Picture taken with the long-pass filter and the NV diamond.

OLED Speed Measurement

- Evaluation of switching speeds for pulsed measurement schemes[4]
- OLEDs were driven with high-speed microdisplay[5] to determine switching times
- Response times (rise + fall):
  - Red: 7.67 µs
  - Green: 7,98 µs
  - Blue: 4,59 µs

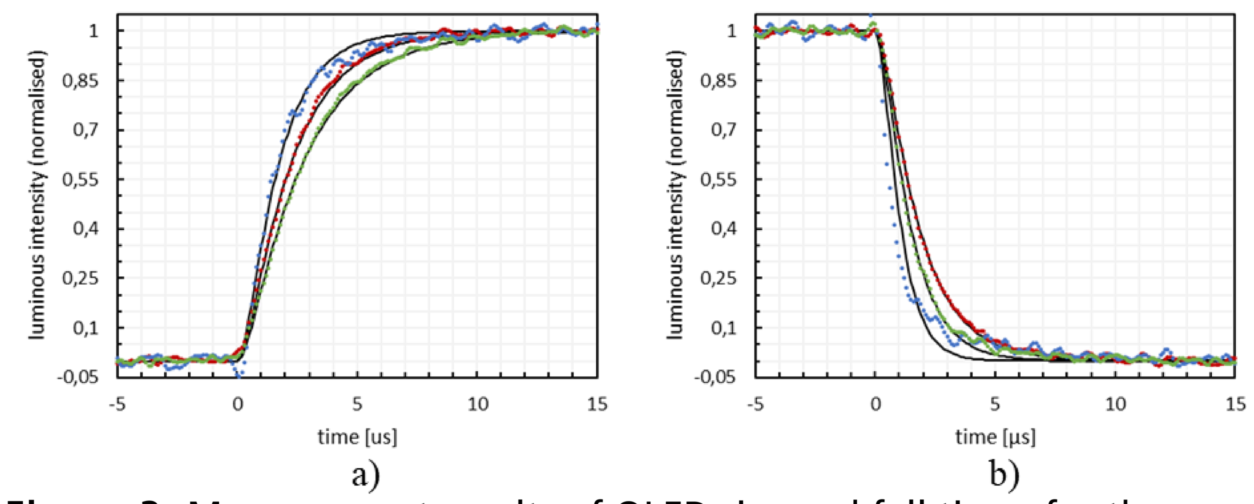

Figure 3. Measurement results of OLED rise and fall times for the different OLED colors (line color according to OLED emission color). a) Fitted functions for rise time. b) Fitted functions for fall time.

Technology Demonstrator

- Test vehicle for:
  - OLED optimization
  - NV diamond optimization
  - Investigation of material / technology interface between OLED-on-silicon and NV diamond technology
- Integrates antenna[6] and µOLED (300 x 350 µm) to excite NV centers in diamond
- Clearly visible red fluorescence could be shown due to optical excitation of NV centers by µOLED

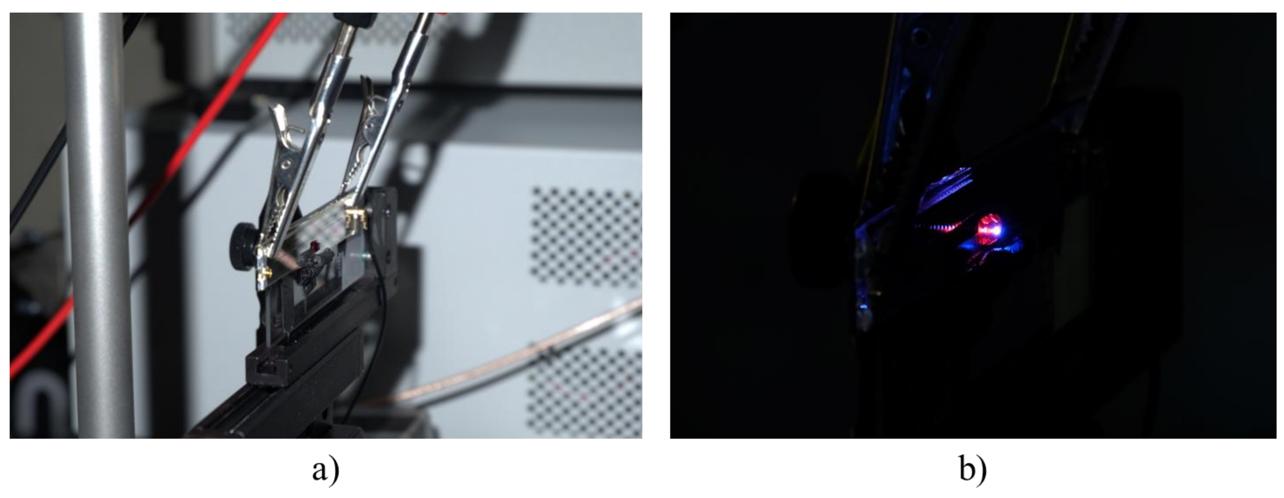

Figure 4. Experimental setup. a) Technology demonstrator with attached NV diamond mounted in the experimental setup. b) Visible red fluorescence of the NV diamond due to the optical excitation of the µOLED.

4. Conclusion and Future Work

The results establish OLED-on-silicon as a strong base technology for the full CMOS integration of optical quantum sensor systems and highlight its potential to push the miniaturization to a new level by placing optical emitters, detectors and MW elements within the same µm-scale footprint. The experiments demonstrate that an OLED-on-silicon platform co-integrated with CMOS provides sufficient brightness, spectral control, and microsecond-scale switching to excite NV centers and detect their fluorescence on-chip within a bidirectional sensor architecture. Beyond size reduction, CMOS offers decisive advantages, like mature, scalable and cost-efficient manufacturing; high yield and reproducibility; dense integration of low-noise analog front-ends, MW drivers, digital control and data processing circuits; low power; array scalability with high fill factor; wafer-level test and calibration. Together, these capabilities position OLED-on-silicon platforms together with CMOS to transition NV-based quantum sensors from lab-scale modules to compact, manufacturable systems.

Future work will include optically detected magnetic resonance (ODMR) measurements with the technology demonstrator, study of integration principles and the material interface between the OLED-on-silicon stack and the NV diamond and finally, the full CMOS integration of a complete optical quantum sensor system.

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