Physikalisch-Technische Bundesanstalt
National Metrology Institute

Justus Christinck[1], Franziska Hirt[1], Helmuth Hofer[1], Zhe Liu[2], Markus Etzkorn[2], Toni Dunatov[3], Milko Jakšić [3], Jacopo Forneris[4], Stefan Kück[1]

Single-photon emitters based on germanium-vacancy centers in solid immersion lenses in diamond

Introduction

Single-photon sources have promising applications, e.g., in low photon-flux radiometry.

$$\phi = \frac{N}{t} h\nu$$

Optical power → ϕ; $\frac{N}{t}$ ← Photons per time; $h\nu$ ← Photon energy

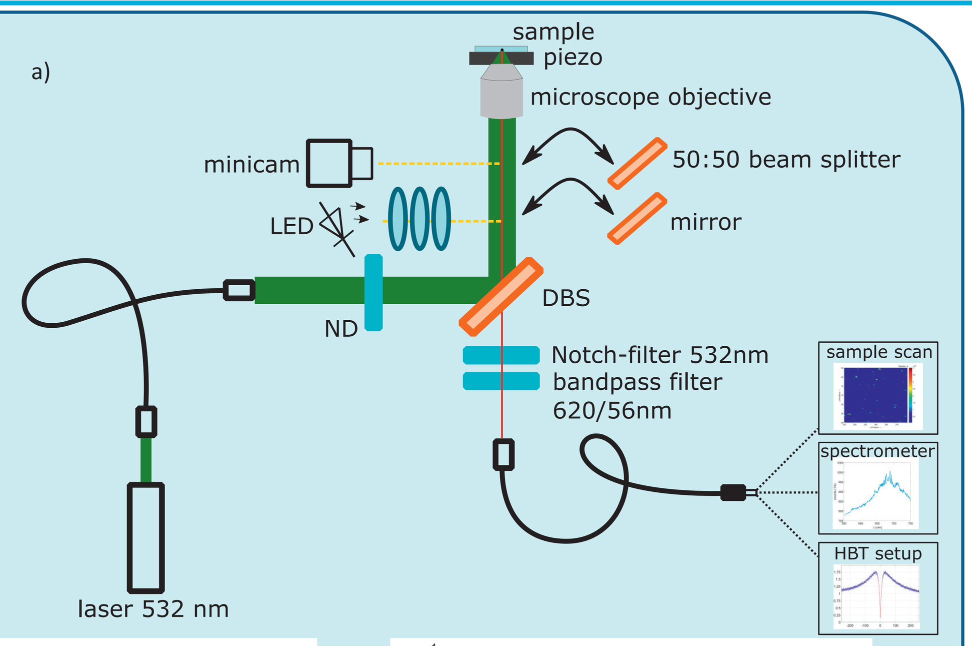
Color centers in diamond are of strong interest in this area due to their stability and the possibility to use them at room temperature.

We present the metrological characterization of the emission of germanium-vacancy (GeV-) centers in diamond in terms of its single-photon purity, saturation behavior and spectral distribution.

The brightness of such sources is of crucial significance for many applications and therefore, a method to enhance the single-photon flux via the fabrication of solid immersion lenses (SILs) on top of the GeV-centers is investigated.

Confocal microscope setup

- Confocal microscope setup for the metrological characterization of single-photon emitters using a 532 nm (cw / up to 80 MHz pulsed) laser and a 50x air objective (NA 0.95).
- Spectral filtering between 592 nm and 648 nm using a bandpass-filter
- SPAD, Hanbury Brown and Twiss interferometer & spectrometer for analysis of the emission
- Timing jitter of the detection system: FWHM = (702 ± 5) ps → see Fig 1.



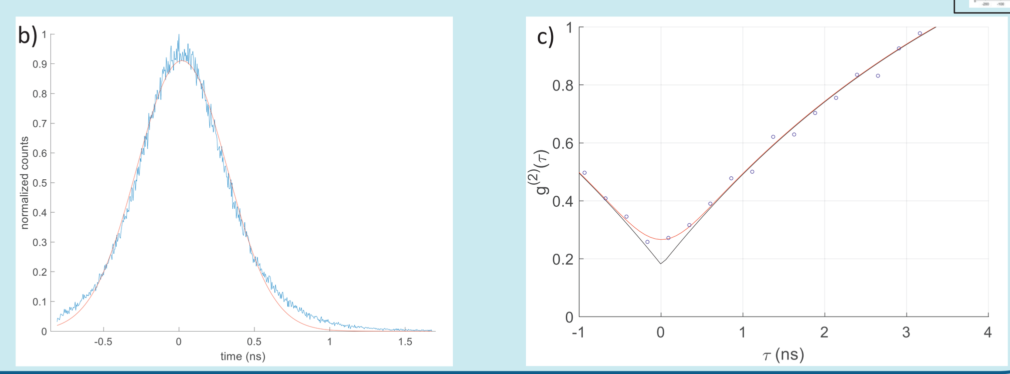
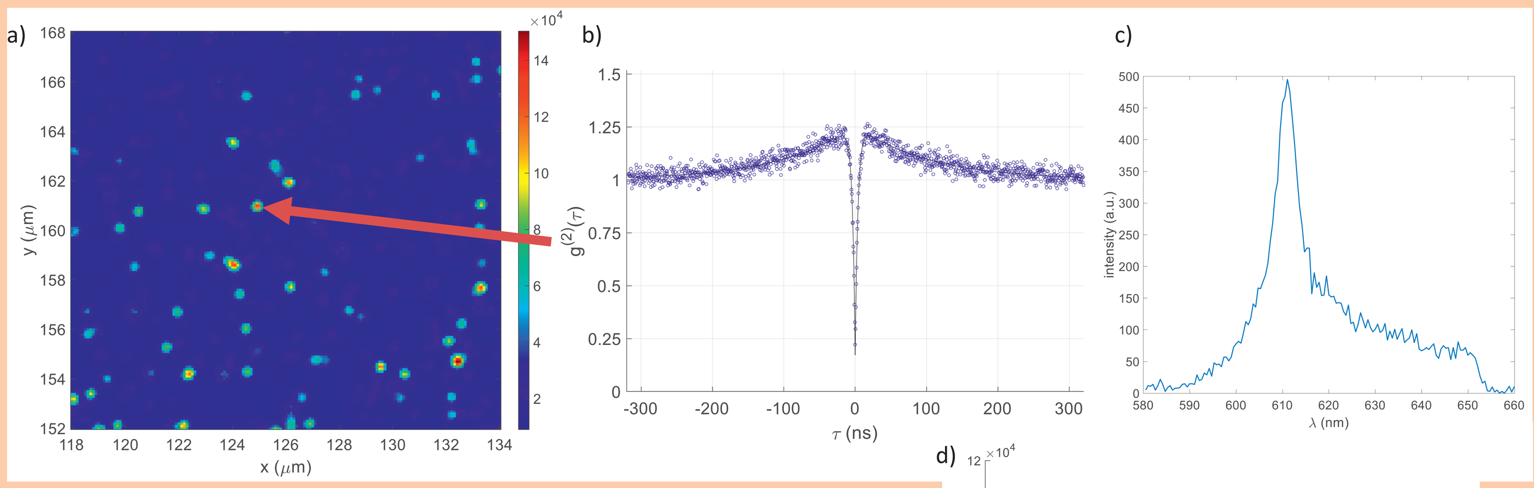


Fig. 1: a) The confocal microscope setup, b) the measured instrument response function and c) its effect on $g^{(2)}$ fitting.

GeV-center fabrication & characterization

- Ge-ions were implanted into a 2 mm x 2 mm diamond with subsequent 1200 °C annealing for 2 h to form GeV-centers.
- The sample was cleaned in an acid bath of 98 % sulfuric acid and 70 % nitric acid (3:1) for 72 h to oxidize the diamond surface and to reduce background.
- An emitter with a ZPL at 610 nm (FWHM 5 nm) was further investigated further.
- A $g^{(2)}(0)$ = 0.17 ± 0.04 was found, showing a significant enhancement of single-photon purity compared to non-acid-treated GeV-centers.
- Saturation power is (3.6 ± 1.2) mW, while the saturation count rate at the detector is (265 ± 65) kcps.



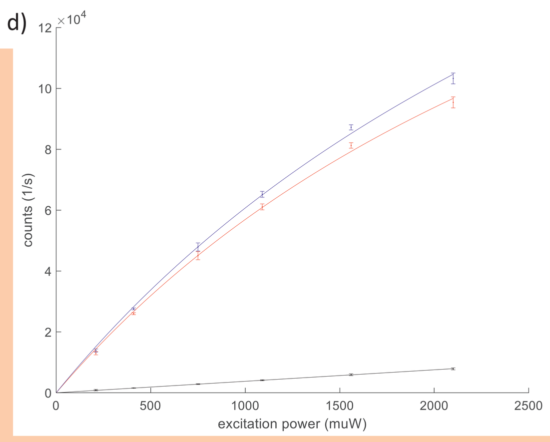


Fig. 2: a) PL map of the GeV sample with the investigated emitter marked with the arrow, b) the $g^{(2)}$ measurement of the emission of this GeV-center, c) its spectral distribution and d) saturation curve.

Solid immersion lens fabrication

The extraction of photons from diamond is severely limited by the high refractive index of the diamond resulting in total internal reflection and refraction into high angles. A solution to this problem is to mill the diamond surface, hence forming a semi-hemispherical SIL (see Fig. 3).

SILs were milled into the diamond using a crossbeam focused ion beam (FIB) setup with an integrated scanning electron microscope (SEM). Two sets of SILs were milled: first with a radius of 1 µm and second with a radius of 0.5 µm into a pre-defined area, where 0.5 µm of diamond was removed beforehand to match emitter depth and SIL radius (see Fig. 4).

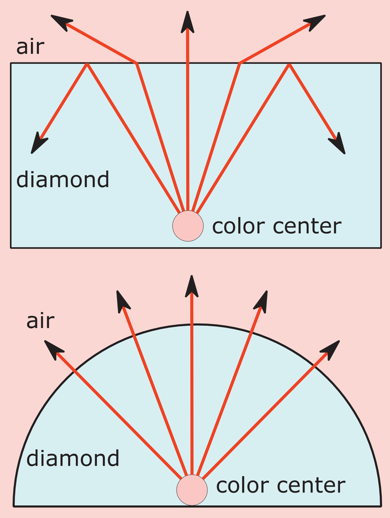


Fig. 3: The principle of a semi-hemispherical solid immersion lens in diamond.

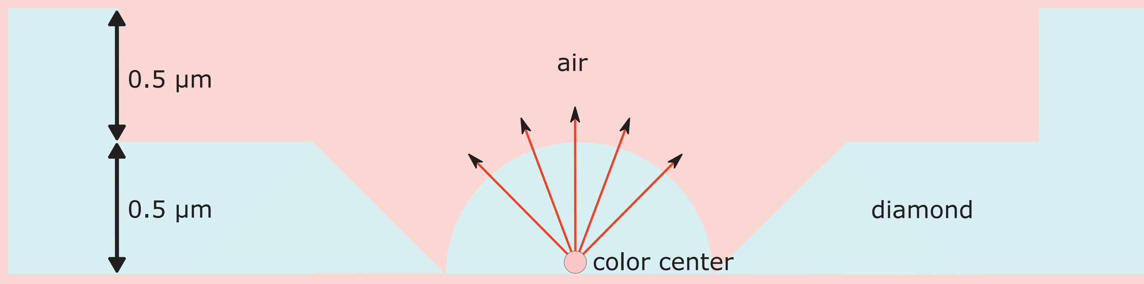


Fig. 4: The 0.5 µm-SILs are milled into a pre-milled hole of 0.5 µm.

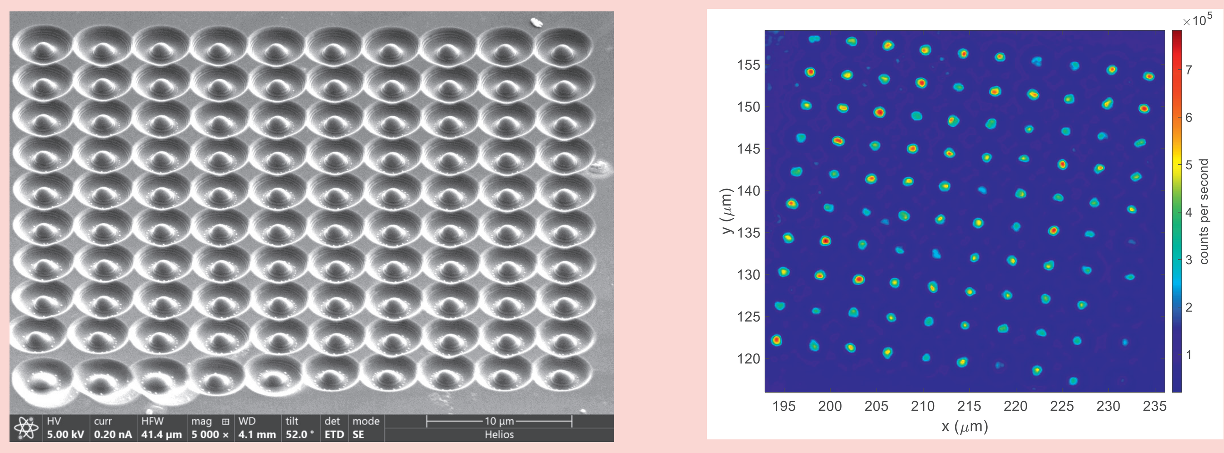


Fig. 5: SEM image of R = 1 µm SIL array and PL map of the same area.

Characterization of SIL emission

The marked SIL in the PL map (Fig. 6a) was further investigated, where a $g^{(2)}(0)$ of 0.53 ± 0.02 was found for cw excitation at roughly 2 mW (b) and $g^{(2)}(0)$ = 0.41 ± 0.01 for pulsed excitation with f_{rep} = 20 MHz and an average power of 0.1 mW (c). The spectral distribution reveals the GeV ZPL at 604.5 nm and the phonon-sideband up to 650 nm, where it is cut off by spectral filtering (d). The lifetime measurement (e) is most accurately fit with a dominant (6.64 ± 0.03) ns lifetime, which is attributed to the excited state of the GeV-center and a secondary (52 ± 14) ps lifetime of unknown origin.

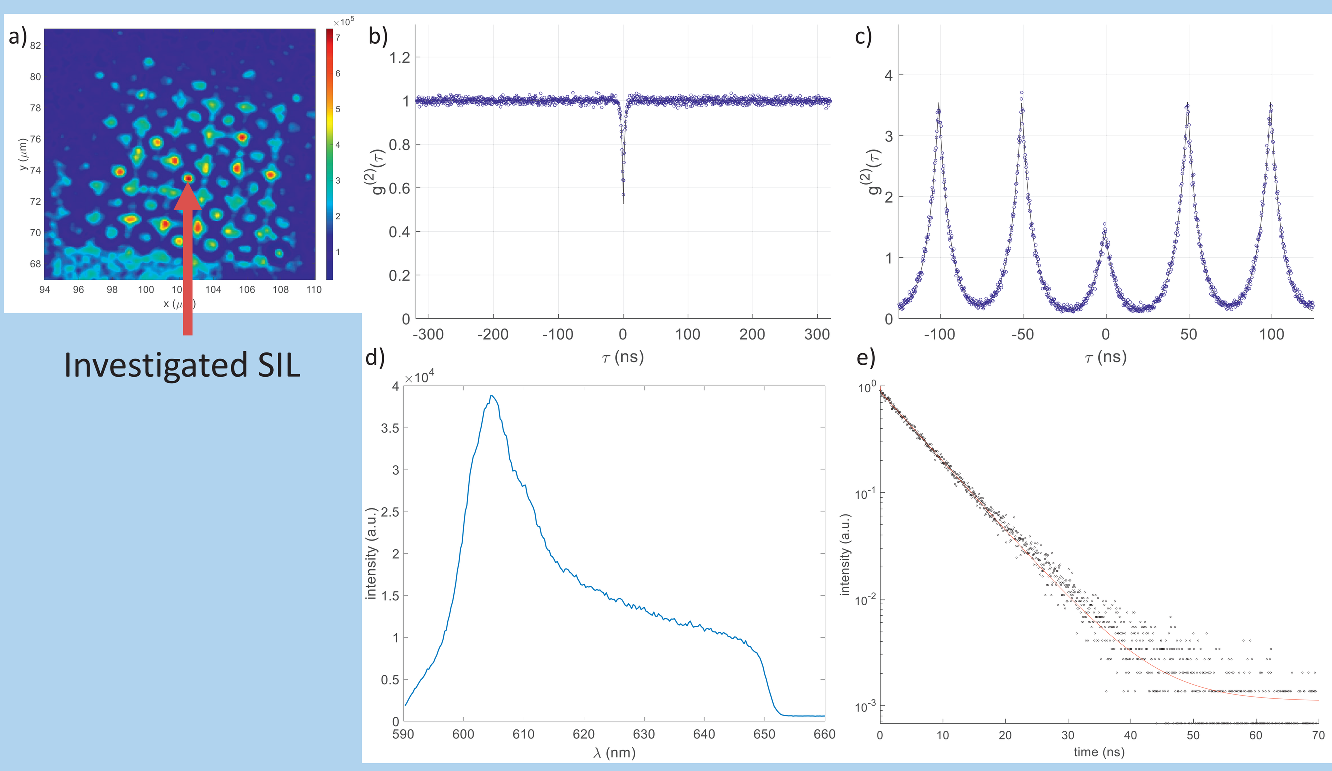


Fig. 6: a) PL map of R = 0.5 µm lens array, with one lens marked, where b) cw $g^{(2)}$ measurement, c) pulsed (f_{rep} = 20 MHz) $g^{(2)}$ measurement, d) spectral distribution and e) lifetime measurement.

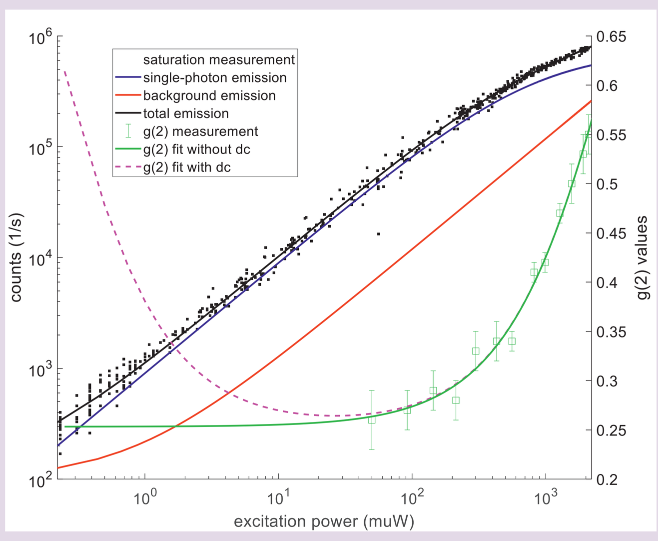
Saturation model

For the analysis of the saturation behavior of the GeV emission the following equation for the count rate is used:

$$N(P) = \frac{N_{sat} P}{P + P_{sat}} + m\,P + dc$$

where N_{sat} is the saturation count rate, P_{sat} is the saturation power, m is the linear background factor, dc the dark count rate of the detector and P the excitation power. Direct measurement of the linear background part is not available for SILs since the background is not homogeneous on the sample. A method involving the excitation power dependent $g^{(2)}$ values was used, where the $g^{(2)}$ is separated into a single-photon part 'a' and background with $g^{(2)}(0)$ = 1 called 'b':

$$g^{(2)}_{a,b} = \frac{g^{(2)}_a a^2 + 2ab + b^2}{(a+b)^2}$$



Using $a = \frac{N_{sat} P}{P + P_{sat}}$ and $b = m\,P + dc$ the results from fitting both functions are

$N_{sat} = (0.75\ \pm 0.01)\ \times\ 10^6 \frac{\text{counts}}{\text{s}}$, which equals 1.5 Mcps in saturation w/o 50:50 beam splitter, which was used here.

$P_{sat} = (0.82\ \pm 0.02)$ mW

$m = (118\ \pm\ 10) \times 10^6 \frac{\text{counts}}{\text{mW} \times \text{s}}$

$g^{(2)}_a = 0.046\ \pm 0.030$

→ 6x enhancement of brightness compared to non-SIL emitter.

Fig. 7: Results of combined fits of saturation behavior of the GeV-center and the excitation power dependent $g^{(2)}$.

Outlook

- Reduction of linear background: thermal annealing, selective SIL placement, …
- Other color centers: SnV, PbV, …

Acknowledgement

This project (EMPUR 20FUN05 SEQUME) has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's 2020 research and innovation programme. This work was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2123 QuantumFrontiers, Project-ID 390837967. We gratefully acknowledge the support of the Braunschweig International Graduate School of Metrology B-IGSM and the DFG Research Training Group 1952 Metrology for Complex Nanosystems.

Physikalisch-Technische Bundesanstalt
National Metrology Institute

Bundesallee 100
38116 Braunschweig, Germany
www.ptb.de

Justus Christinck
Working Group 4.55
Single-photon Metrology Radiometry at LENA
phone: +49 531 592-4121
e-mail: justus.christinck@ptb.de

1 Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
2 TU Braunschweig, Braunschweig, Germany
3 Ruđer Bošković Institute, Zagreb, Croatia
4 University of Torino, Torino, Italy