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Heterodyne detection of radio-frequency electric fields using point defects in silicon carbide

G. Wolfowicz et al. (2019). “Heterodyne detection of radio-frequency electric fields using point defects in silicon carbide”. In: *Applied Physics Letters* 115.4, p. 043105.

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Motivation

- Measurements of utmost importance in (experimental) physics
- Not only quantity x, but also
  - Information about vector field: $\vec{x}$
  - Spatial distribution: $\vec{x}(\vec{r})$
  - Time (and frequency) domain: $x(t)$, $X(f)$
  - Gradients: $\nabla\vec{x}(\vec{r})$

Figure: Measurements in physics.[1]

[1] https://www.helpyoubetter.com/measurement-in-physics-and-si-units-of-measurement/amp/, acessed 28.04.2021

Electrometry

Existing technologies:

- Field mill (Sensitivity $200\,\mathrm{V\,m^{-1}}$)
- Nitrogen-vacancies in diamonds
- Spin-based sensing (comparable to method presented here)
- Quantum dots

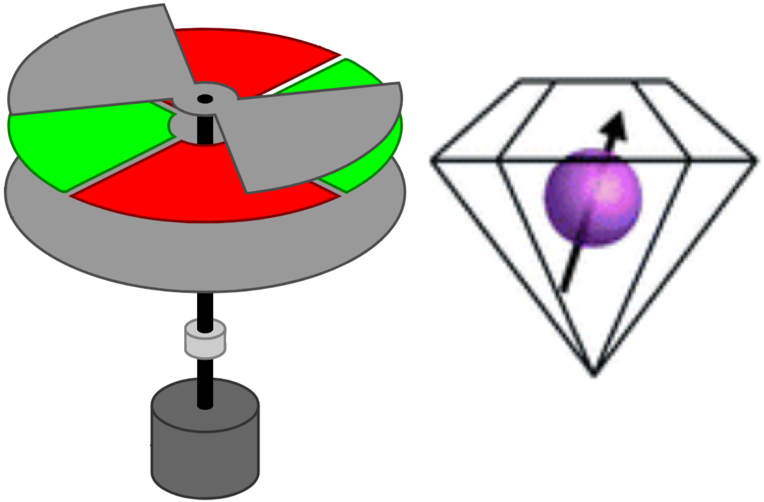

Figure: Field mill (left) and spin-based sensing (right).[2]

[2] after https://upload.wikimedia.org/wikipedia/commons/9/99/Signalverarbeitung-Feldm%C3%BChle.svg, acessed 25.04.2021 and https://pubs.rsc.org/ko/content/articlelanding/2019/ra/c9ra02282a#!divAbstract, acessed 28.04.2021

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Silicon carbide and vacancies

- Silicon-carbon-lattice
- Used in high-endurance applications
- Semiconductor industry: high temperature and/or voltage applications
- Increased interest as vacancy-based sensor

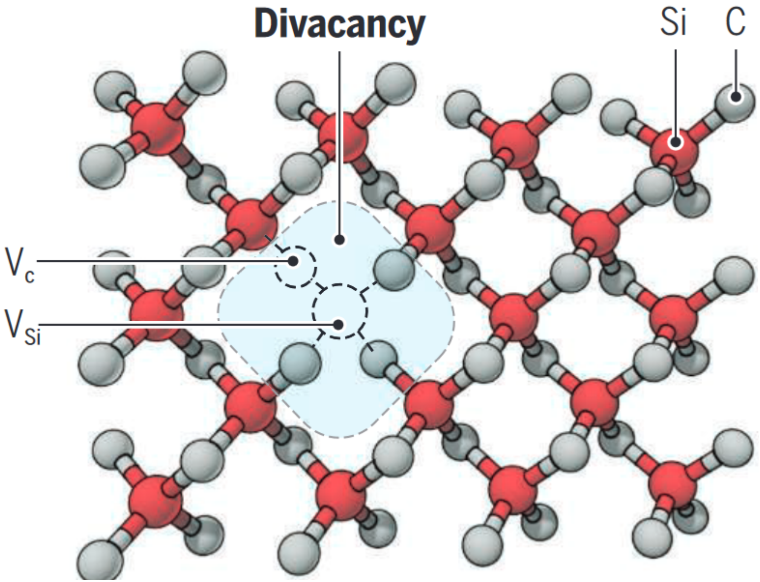

Figure: Divacancy in silicon carbide.[3]

[3] A. L Falk (2017). "Adressing spin states with infrared light". In: *Science* 357.6352, pp. 649-649

Silicon carbide and vacancies

- e^- on vacancy positions: Different spin and charge states
- Only charge states VV^0 shows photoluminescence (PL) $\rightarrow$ Optical detection with suitable laser excitation

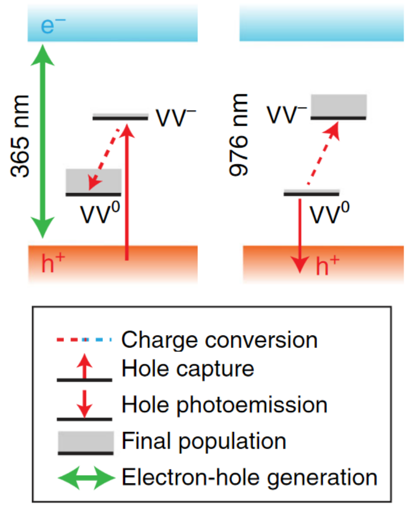

Figure: Energy level scheme of divacancy.[4]

[4] after Wolfowicz G, Anderson CP, Yeats AL, et al (2017). "Optical charge state control of spin defects in 4H-SiC". In: *Nat Commun.* 8(1):1876. Published 2017 Nov 30.

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Measurement protocol

- Measurement: Repump divacancies with reset laser
- Data acquisition while illumination with readout laser
- Contrast value: $\frac{\mathrm{PL}(E)-\mathrm{PL}(E=0)}{\mathrm{PL}(E=0)}$

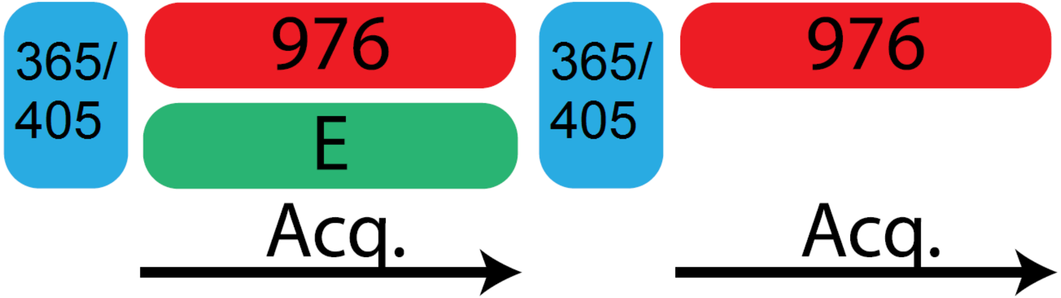


Figure: Measurement protocol.[5]

[5] after G. Wolfowicz, S. J. Whiteley, and D. D. Awschalom (2018). “Electrometry by optical charge conversion of deep defects in 4H-SiC” PNAS 115.31, pp. 7879–7883.

Silicon carbide and vacancies

- Fit function for contrast contains rate shift $\Delta R(E) = \Delta R_\infty \left\langle \frac{(E/E_{\text{sat}})^2}{1+(E/E_{\text{sat}})^2} \right\rangle_t$, is E-dependent
- Sensitivity $S = \frac{E^2 \sigma_{\Delta PL}(E)\sqrt{t_{\text{exp}}}}{\Delta \text{PL}(E)}$

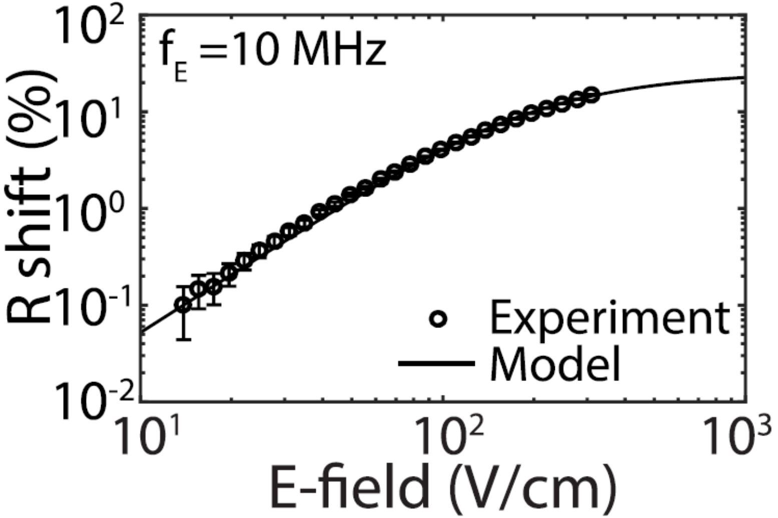


Figure: Shift of rate R.[6]

[6] G. Wolfowicz, S. J. Whiteley, and D. D. Awschalom (2018). “Electrometry by optical charge conversion of deep defects in 4H-SiC”. In: *Proceedings of the National Academy of Sciences* 115.31, pp. 7879–7883.

Experimental setup

- Ensemble of divacancies created via carbon implantation
- Optical detection and pumping by lasers: EOCC (Electrometry by optical charge conversion)
- Application of sensed field $\vec{E}_{\text{sensed}}$ and pump field $\vec{E}_{\text{pump}}$ through titan-/gold-contacts
- Signal strength S proportional to quadratic electrical field $\vec{E}^2$

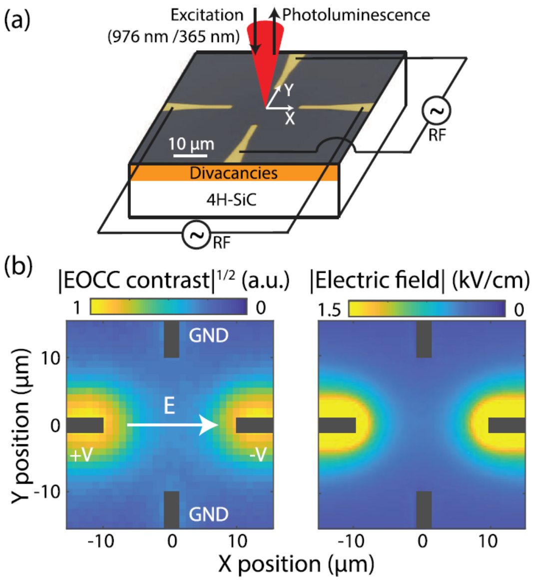


Figure: a) Experimental setup of the sensor b) Measurement (left) and simulation (right).

Experimental setup - Heterodyne

Consider $S \propto \vec{E}^2 =$
$(E_{\text{pump}} \cos(\omega_{\text{pump}} t)\vec{u}_p + E_{\text{sensed}} \cos(\omega_{\text{sensed}} t + \phi)\vec{u}_s)^2$
with $\vec{u}_p$, $\vec{u}_s$ normalized vectors
$\rightarrow$ mixed term $\propto E_{\text{pump}} E_{\text{sensed}} \cos(\Delta\omega t + \phi)\vec{u}_p\vec{u}_s$

- Scalar product: Alignment information
- Linear in E_{sensed} $\rightarrow$ increased sensitivity for low electrical fields

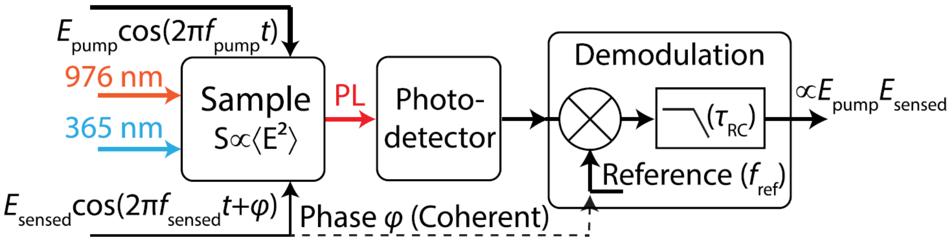


Figure: Electronics of the device.

Applications - Spectroscopy

- Sweep of reference frequency f_{ref} of lock-in
- FWHM only limited by lock-in acquisition time $\tau_{\mathrm{RC}} \rightarrow$ Improvement over comparable methods

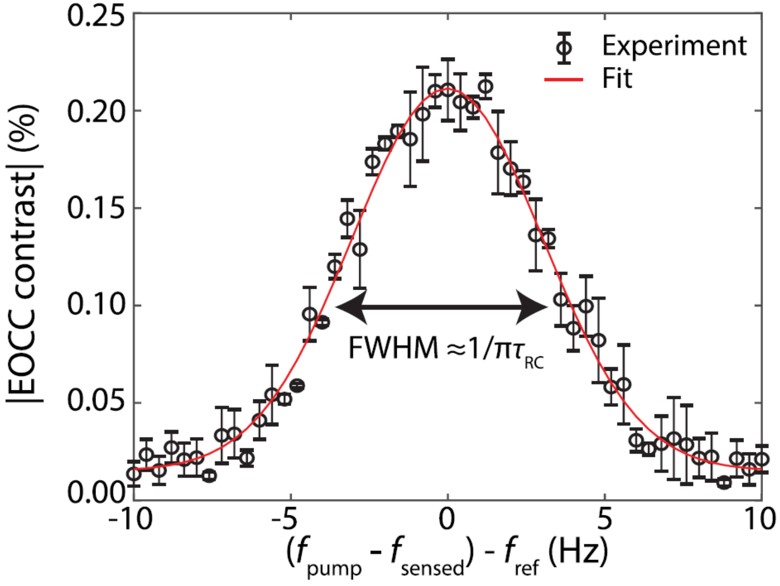


Figure: Spectroscopic potential of the device.

Applications - Contrast of heterodyne

- Higher pump field $\rightarrow$ higher contrast (possible limit: saturation)
- Standard EOCC: Quadratic response, low sensitivity for small E_{sensed}
- Heterodyne measurement: Linear in E, higher sensitivity. Coherent heterodyne (ϕ fixed): Signal extended to noise floor

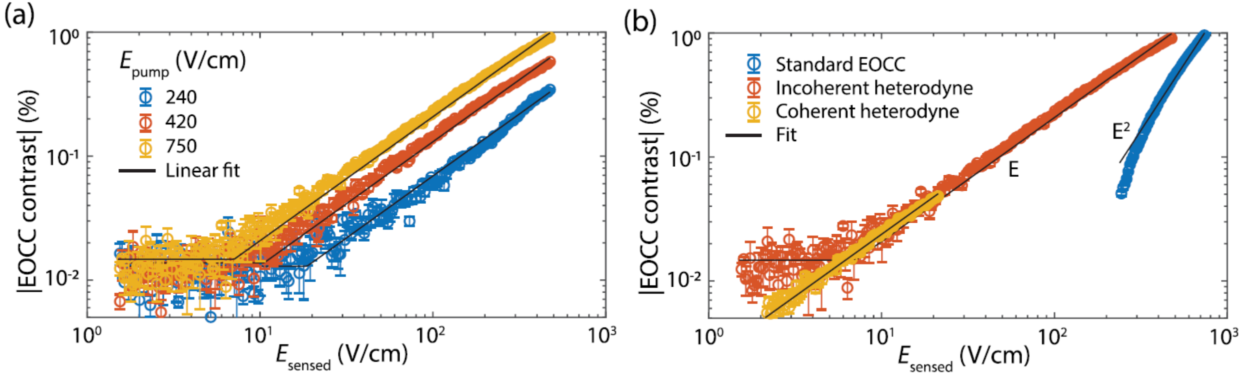


Figure: a) Effect of pump field E_{pump}; b) Quadratic EOCC response vs. (in)coherent heterodyne.

Applications - phase information

- Signal at $\Delta\omega$ proportional to scalar product $\vec{u}_p \cdot \vec{u}_s \rightarrow$ Cancels out when fields are orthogonal
- 2D-vector information can be read of

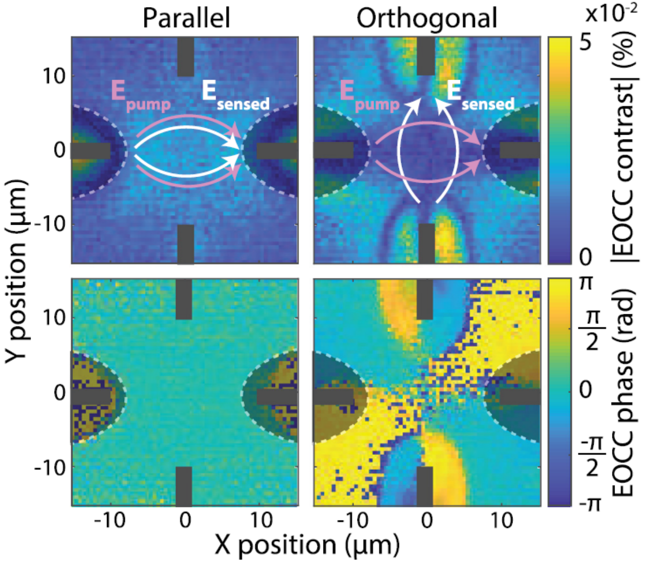


Figure: Parallel (left) and orthogonal (right) configuration. Bottom row: Phase contrast.

Sensitivity

- Sensitivity of 1.1 $(\mathrm{V/cm})/\sqrt{\mathrm{Hz}}$ for $\approx 10^3$ to 10^4 defects $\rightarrow$ Thinning out divacancies: Higher spatial resolution; more vacancies: Better sensitivity
- Better per defect than spin-based sensing (0.1 $(\mathrm{V/cm})/\sqrt{\mathrm{Hz}}$ for 10^{11} defects, 200 $(\mathrm{V/cm})/\sqrt{\mathrm{Hz}}$ for a single defect)
- Comparison to semiconductor technologies: $10^4\,\mathrm{V\,cm^{-1}}$
  Cavity quantum electrodynamics[7]: $2\,\mathrm{mV\,cm^{-1}}$

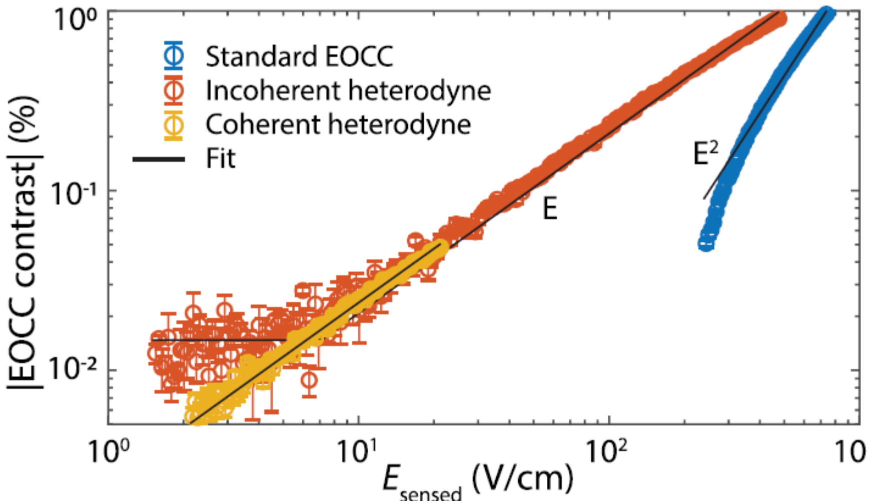
[7] A. Blais et al. (2004). "Cavity quantum electrodynamics for superconducting electrical circuits: An architecture for quantum computation". In: *Phys. Rev. A* 69 (6), p. 062320.

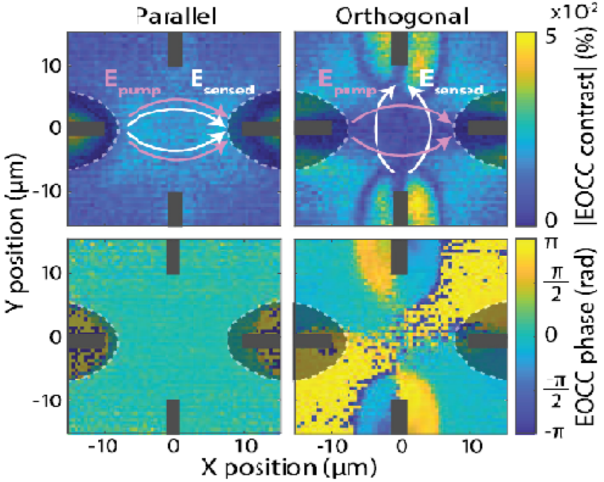
Outlook

- 3D information by applying a pump field orthogonal to substrate
- Multifrequency pumps for sensing different frequencies of the electrical field
- Alternative defects better suited for EOCC measurements

Conclusion

- Vacancies in silicon carbide accessed via charge-based measurements allow for sensing applications of electrical field
- Nonlinear response to $\vec{E}$ enables heterodyne techniques $\rightarrow$ higher sensitivity, lower $\vec{E}$-values accessible, phase and vector information
- Presented technique better than spin-based sensing; can be adjusted to individual needs





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Thank you for your attention!