REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY) 30-04-2021	2. REPORT TYPE Final Report	3. DATES COVERED (From - To) 1-Jan-2018 - 31-Dec-2020

4. TITLE AND SUBTITLE
Final Report: Engineering diamond quantum optical systems for quantum computing and simulations

5a. CONTRACT NUMBER
W911NF-18-1-0062

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

6. AUTHORS

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES

Stanford University
3160 Porter Drive
Suite 100
Stanford, CA 94304 -8445

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)

U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
71522-PH.24

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Jelena Vuckovic
a. REPORT	b. ABSTRACT	c. THIS PAGE			
UU	UU	UU	UU		19b. TELEPHONE NUMBER 650-725-2288

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

RPPR Final Report
as of 07-May-2021

Agency Code: 21XD

Proposal Number: 71522PH **Agreement Number: W911NF-18-1-0062**

INVESTIGATOR(S):

Name: Jelena Vuckovic jela@stanf
Email: jela@stanford.edu
Phone Number: 6507252288
Principal: Y

Organization: **Stanford University**
Address: 3160 Porter Drive, Stanford, CA 943048445
Country: USA

DUNS Number: 009214214 EIN: 941156365
Report Date: 31-Mar-2021 Date Received: 30-Apr-2021
Final Report for Period Beginning 01-Jan-2018 and Ending 31-Dec-2020
Title: Engineering diamond quantum optical systems for quantum computing and simulations
Begin Performance Period: 01-Jan-2018 **End Performance Period:** 31-Dec-2020
Report Term: 0-Other
Submitted By: Jelena Vuckovic Email: jela@stanford.edu
Phone: (650) 725-2288
Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 1 **STEM Participants:** 2

Major Goals: The goal of this proposal is to leverage the exceptional optical properties of the Silicon-Vacancy (SiV) and Tin-vacancy (SnV) color centers in diamond and to develop devices for quantum computing and simulation on diamond nanophotonic platform. We aim to expand on our diamond fabrication toolbox and produce a new generation of nanostructures capable of reaching high-level control over the phonon processes that currently restrict the spin coherence in color centers. This would represent a significant advance in the development of high-fidelity spin-photon interfaces. Furthermore, our plan is to develop photonic crystal cavities that host one or multiple SiV and SnV centers and could operate in the strong coupling regime. Due to the small inhomogeneous broadening in these color centers, such devices would be excellent candidates for studies of many body interactions and implementations of new quantum simulation paradigms. The proposed program will include the following activities:

- Design and fabrication of nanophotonic structures which can modify local phonon density of states or induce large strain, both of which could significantly improve the coherence time of a single embedded SiV;
- Development of a full set of single qubit operations of SiV and SnV spins using all-optical pulses, which could improve the single qubit operation speed by three orders of magnitude;
- Development of new fabrication methods that can enable high quality factor and small mode volume cavities in diamond;
- Demonstration of strong coupling between a single SiV or SnV center and / or a few SiV or SnV centers and a nanophotonic cavity;
- Study of applications of SiV and SnV center based cavity QED systems, including photon blockade, non-classical light generation, and quantum simulations.

Accomplishments: We have made significant progress on the following topics, as described in details in the attached research report (pdf file):

1. Site-Controlled Generation of SnV– Centers in Diamond via Shallow Ion Implantation and Growth
2. Narrow-Linewidth SnV– Centers coupled to Diamond Waveguides

3. Cavity QED with SnV centers coupled to diamond cavities

4. Stark tuning of SnV in diamond

RPPR Final Report
as of 07-May-2021

Training Opportunities: As part of this program, involved students and postdocs have been trained on state of the art equipment in the lab of the PI. The PI has developed and successfully taught several classes related to the topic of this project, including a popular graduate class on Optical Micro- and Nanocavities.
Our postdoc Shuo Sun who worked on this project joined physics faculty at UC Boulder and JILA, and our PhD student Constantin Dory who was involved with this project graduated and joined Apple.

Results Dissemination: Research results and publications are regularly disseminated on arxiv.org and website of the PI's research group, http://nqp.stanford.edu/, as well as at conferences, workshops and seminars.

Honors and Awards: - Jelena Vuckovic, James P. Gordon Memorial Speaker, the Optical Society - OSA (2020)
- Jelena Vuckovic, IET Harvey Prize (2019)
- Jelena Vuckovic, Distinguished Scholar of the Max Planck Institute for Quantum Optics (2019)
- Constantin Dory, Microsoft Research PhD Fellowship (2019-2021)
- Alison Rugar, National Defense Science and Engineering Graduate (NDSEG) Fellowship
- Shahriar Aghaeimeibodi, Bloch Postdoctoral Fellowship in Quantum Science and Engineering, Stanford University

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: Jelena Vuckovic
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Shuo Sun
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Constantin Dory
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Alison Rugar
Person Months Worked: 9.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Daniel Riedel
Person Months Worked: 6.00 **Funding Support:**

Project Contribution:
National Academy Member: N

ARTICLES:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Nano Letters
Publication Identifier Type: DOI Publication Identifier: 10.1021/acs.nanolett.7b05075
Volume: 18 Issue: 2 First Page #: 1360
Date Submitted: 7/31/18 12:00AM Date Published: 2/1/18 4:00PM
Publication Location:
Article Title: Strongly Cavity-Enhanced Spontaneous Emission from Silicon-Vacancy Centers in Diamond
Authors: Jingyuan Linda Zhang, Shuo Sun, Michael J. Burek, Constantin Dory, Yan-Kai Tzeng, Kevin A. Fischer,
Keywords: Purcell enhancement, single-photon generation, defect-center materials, diamond, silicon-vacancy center, nanophotonics, color center
Abstract: Quantum emitters are an integral component for a broad range of quantum technologies, including quantum communication, quantum repeaters, and linear optical quantum computation. Solid-state color centers are promising candidates for scalable quantum optics due to their long coherence time and small inhomogeneous broadening. However, once excited, color centers often decay through phonon-assisted processes, limiting the efficiency of singlephoton generation and photon-mediated entanglement generation. Herein, we demonstrate strong enhancement of spontaneous emission rate of a single silicon-vacancy center in diamond embedded within a monolithic optical cavity, reaching a regime in which the excited-state lifetime is dominated by spontaneous emission into the cavity mode. We observe 10-fold lifetime reduction and 42-fold enhancement in emission intensity when the cavity is tuned into resonance with the optical transition of a single silicon-vacancy center.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optica
Publication Identifier Type: DOI Publication Identifier: 10.1364/OPTICA.4.001317
Volume: 4 Issue: 11 First Page #: 1317
Date Submitted: 7/31/18 12:00AM Date Published: 10/1/17 12:00AM
Publication Location:
Article Title: Complete coherent control of silicon vacancies in diamond nanopillars containing single defect centers
Authors: Jingyuan Linda Zhang, Konstantinos G. Lagoudakis, Yan-Kai Tzeng, Constantin Dory, Marina Radulask
Keywords: Defect-center materials, Quantum optics, Coherent optical effects
Abstract: Arrays of identical and individually addressable qubits lay the foundation for the creation of scalable quantum hardware such as quantum processors and repeaters. Silicon-vacancy (SiV) centers in diamond offer excellent physical properties such as low inhomogeneous broadening, fast photon emission, and a large Debye–Waller factor. The possibility for all-optical ultrafast manipulation and techniques to extend the spin coherence times makes them promising candidates for qubits. Here, we have developed arrays of nanopillars containing single (SiV) centers with high yield, and we demonstrate ultrafast all-optical complete coherent control of the excited state population of a single SiV center at the optical transition frequency. The high quality of the chemical vapor deposition (CVD) grown SiV centers provides excellent spectral stability, which allows us to coherently manipulate and quasi-resonantly read out the excited state population of individual SiV centers on picosecond timescales.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevLett.121.083601
Volume: 121 Issue: First Page #: 083601
Date Submitted: 5/27/19 12:00AM Date Published: 8/21/18 2:00PM
Publication Location:
Article Title: Cavity-enhanced Raman emission from a single color center in a solid
Authors: Shuo Sun*, Jingyuan Linda Zhang*, Kevin A. Fischer*, Michael J. Burek, Constantin Dory, Konstantinos
Keywords: color center, quantum information, Raman scattering
Abstract: We demonstrate cavity-enhanced Raman emission from a single atomic defect in a solid. Our platform is a single silicon-vacancy center in diamond coupled with a monolithic diamond photonic crystal cavity. The cavity enables an unprecedented frequency tuning range of the Raman emission (100 GHz) that significantly exceeds the spectral inhomogeneity of silicon-vacancy centers in diamond nanostructures. We also show that the cavity selectively suppresses the phonon-induced spontaneous emission that degrades the efficiency of Raman photon generation. Our results pave the way towards photon-mediated many-body interactions between solid-state quantum emitters in a nanophotonic platform.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review B
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevB.99.205417
Volume: 99 Issue: First Page #: 205417
Date Submitted: 5/27/19 12:00AM Date Published: 5/16/19 2:00PM
Publication Location:
Article Title: Characterization of Optical and Spin Properties of Single Tin-Vacancy Centers in Diamond Nanopillars
Authors: Alison E. Rugar, Constantin Dory, Shuo Sun, Jelena Vu?kovi?
Keywords: diamond, color centers, tin vacancy, quantum photonics
Abstract: Color centers in diamond have attracted much interest as candidates for optically active, solid-state quantum bits. Of particular interest are inversion-symmetric color centers based on group-IV impurities in diamond because they emit strongly into their zero-phonon lines and are insensitive to electric field noise to first order. Early studies of the negatively charged tin-vacancy (SnV?) center in diamond have found the SnV? to be a promising candidate: it has high quantum efficiency, emits strongly into its zero-phonon lines, and is expected to have a long T2 spin coherence time at 4 K. To develop the SnV? into a spin qubit requires further characterization, especially of the spin and optical properties of individual SnV? in nanofabricated structures. In this work, we isolate single SnV? centers in diamond nanopillars and characterize their emission properties and their spin response to a magnetic field. We observe narrow emission linewidths <250 MHz, as well as a strong polarization
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 4-Under Review
Journal: Physical Review X
Publication Identifier Type: Other Publication Identifier: arxiv:2102.11852
Volume: Issue: First Page #:
Date Submitted: 4/30/21 12:00AM Date Published:
Publication Location:
Article Title: A Quantum Photonic Interface for Tin-Vacancy Centers in Diamon
Authors: Alison E. Rugar, Shahriar Aghaeimeibodi, Daniel Riedel, Constantin Dory, Haiyu Lu, Patrick J. McQuad
Keywords: cavity QED, DnV, diamond, quantum networks, quantum optics

Abstract: The realization of quantum networks critically depends on establishing efficient, coherent light-matter interfaces. Optically active spins in diamond have emerged as promising quantum nodes based on their spin-selective optical transitions, long-lived spin ground states, and potential for integration with nanophotonics. Tin-vacancy (SnV-) centers in diamond are of particular interest because they exhibit narrow-linewidth emission in nanostructures and possess long spin coherence times at temperatures above 1 K. However, a nanophotonic interface for SnV- centers has not yet been realized. Here, we report cavity enhancement of the emission of SnV- centers in diamond. We integrate SnV- centers into one-dimensional photonic crystal resonators and observe a 40-fold increase in emission intensity. The Purcell factor of the coupled system is 25, resulting in channeling of the majority of photons (90%) into the cavity mode. Our results pave the way for the creation of efficient, scalable spin-

Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 4-Under Review
Journal: Physical Review Applied
Publication Identifier Type: Other Publication Identifier: arXiv:2103.01917
Volume: Issue: First Page #:
Date Submitted: Date Published:
Publication Location:
Article Title: Electrical control of tin-vacancy centers in diamond
Authors: Shahriar Aghaeimeibodi, Daniel Riedel, Alison E. Rugar, Constantin Dory, and Jelena Vuckovic
Keywords: SnV, diamond, Stark tuning, quantum optics, quantum networks

Abstract: Group-IV color centers in diamond have attracted significant attention as solid-state spin qubits because of their excellent optical and spin properties. Among these color centers, the tin-vacancy (SnV-) center is of particular interest because its large ground-state splitting enables long spin coherence times at temperatures above 1K. However, color centers typically suffer from inhomogeneous broadening, which can be exacerbated by nanofabrication-induced strain, hindering the implementation of quantum nodes emitting indistinguishable photons. Although strain and Raman tuning have been investigated as promising techniques to overcome the spectral mismatch between distinct group-IV color centers, other approaches need to be explored to find methods that can offer more localized control without sacrificing emission intensity. Here, we study electrical tuning of SnV-centers in diamond via the direct-current Stark effect. We demonstrate a tuning range beyond 1.7GHz. We observe both quadr

Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

CONFERENCE PAPERS:

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: CLEO: QELS_Fundamental Science
Date Received: 01-Aug-2018 Conference Date: 13-May-2018 Date Published: 13-May-2018
Conference Location: San Jose, California
Paper Title: Strong Cavity Enhancement of Spontaneous Emission from Silicon-Vacancy Centers in Diamond
Authors: Jingyuan Linda Zhang, Shuo Sun, Michael J. Burek, Constantin Dory, Yan-Kai Tzeng, Kevin A. Fischer,
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: CLEO: Applications and Technology
Date Received: 01-Aug-2018 Conference Date: 13-May-2018 Date Published: 13-May-2018
Conference Location: San Jose, California
Paper Title: Diamond Color Center Integration with a Silicon Carbide Photonics Platform
Authors: Marina Radulaski, Yan-Kai Tzeng, Jingyuan Linda Zhang, Hitoshi Ishiwata, Konstantinos G. Lagoudakis
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: CLEO: Science and Innovations
Date Received: 31-Jul-2018 Conference Date: 14-May-2018 Date Published: 14-May-2018
Conference Location: San Jose, California
Paper Title: Optimized photonics: from on-chip nonclassical light sources to circuits
Authors: Jelena Vuckovic, Kevin Fischer, Kai Müller, Jingyuan Linda Zhang, Shuo Sun, Constantin Dory, Rahul T
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: APS March meeting
Date Received: 01-Aug-2018 Conference Date: 05-Mar-2018 Date Published: 05-Mar-2018
Conference Location: Los Angeles, CA
Paper Title: Hybrid Diamond-Silicon Carbide Color Center Photonics
Authors: Marina Radulaski, Yan-Kai Tzeng, Jingyuan Linda Zhang, Konstantinos G. Lagoudakis, Hitoshi Ishiwata
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 2-Awaiting Publica
Conference Name: CQIS- International Conference on Challenges in Quantum Information Science
Date Received: 01-Aug-2018 Conference Date: 09-Apr-2018 Date Published: 09-Apr-2018
Conference Location: Tokyo, Japan
Paper Title: Quantum Nanophotonics
Authors: Jingyuan Linda Zhang, Jelena Vuckovic
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: APS March Meeting
Date Received: 27-May-2019 Conference Date: 04-Mar-2019 Date Published: 04-Mar-2019
Conference Location: Boston, MA, USA
Paper Title: Optical Characterization of Single Tin-Vacancy Centers in Diamond
Authors: Alison Rugar, Constantin Dory, Shuo Sun, Jelena Vuckovic
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: APS March Meeting
Date Received: 27-May-2019 Conference Date: 04-Mar-2019 Date Published: 04-Mar-2019
Conference Location: Boston, MA, USA
Paper Title: Optimized Quantum Photonics in Diamond
Authors: Constantin Dory, Dries Vercruysse, Ki Youl Yang, Neil V. Sapra, Alison E. Rugar, Shuo Sun, Daniil M. L
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: CLEO: QELS_Fundamental Science
Date Received: 27-May-2019 Conference Date: 05-May-2019 Date Published: 05-May-2019
Conference Location: San Jose, California
Paper Title: Inverse Designed Diamond Nanophotonics
Authors: Constantin Dory, Dries Vercruysse, Ki Youl Yang, Neil V. Sapra, Alison E. Rugar, Shuo Sun, Daniil M. L
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: CLEO: QELS_Fundamental Science
Date Received: 27-May-2019 Conference Date: 05-May-2019 Date Published: 05-May-2019
Conference Location: San Jose, California
Paper Title: Optical Characterization of Single Tin-Vacancy Centers in Diamond Nanopillars
Authors: Alison E. Rugar, Constantin Dory, Shuo Sun, and Jelena Vu?kovi?
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: CLEO: QELS_Fundamental Science
Date Received: 27-May-2019 Conference Date: 05-May-2019 Date Published: 05-May-2019
Conference Location: San Jose, California
Paper Title: Frequency Tunable Single-Photon Emission From a Single Atomic Defect in a Solid
Authors: Shuo Sun, Jingyuan Linda Zhang, Kevin A. Fischer, Michael J. Burek, Constantin Dory, Konstantinos G.
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: American Physics Society (APS) March Meeting 2020
Date Received: 24-Aug-2020 Conference Date: 05-Mar-2020 Date Published: 05-Mar-2020
Conference Location: Denver, CO, USA
Paper Title: Site-controlled generation of tin-vacancy centers in diamond via shallow ion implantation and subsequent diamond growth
Authors: Alison E. Rugar, Haiyu Lu, Constantin Dory, Shuo Sun, Patrick McQuade, Zhi-Xun Shen, Nicholas Melo
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Conference on Lasers and Electro-Optics (CLEO)
Date Received: 24-Aug-2020 Conference Date: 05-May-2020 Date Published: 05-May-2020
Conference Location: San Jose, CA, USA
Paper Title: Optical Characterization of Single Tin-Vacancy Centers in Diamond Nanopillars
Authors: Alison E. Rugar, Constantin Dory, Shuo Sun, and Jelena Vu&#x3f;kovi&#x3
Acknowledged Federal Support: **Y**

DISSERTATIONS:

Publication Type: Thesis or Dissertation
Institution: Stanford University
Date Received: 27-May-2019 Completion Date: 6/5/19 5:32PM
Title: QUANTUM ENGINEERING WITH SOLID STATE NANOPHOTONIC SYSTEMS
Authors: Jingyuan Linda Zhang
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 07-May-2021

Publication Type: Thesis or Dissertation
Institution: Stanford University
Date Received: 24-Aug-2020 Completion Date: 5/30/20 10:20PM
Title: Engineering solid-state platforms for quantum photonics
Authors: Constantin Dory
Acknowledged Federal Support: **Y**

Partners

,

I certify that the information in the report is complete and accurate:
Signature: Jelena Vuckovic
Signature Date: 4/30/21 12:53PM

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

Note: 6 pages total

Publications (since the previous interim report)

Published in Peer-Reviewed Journals

1. Alison E. Rugar* Constantin Dory*, Shahriar Aghaeimeibodi*, Haiyu Lu, Shuo Sun, Sattwik Deb Mishra, Zhi-XunShen, Nicholas A. Melosh, Jelena Vuckovic, *Narrow-Linewidth Tin-Vacancy Centers in a Diamond Waveguide*, ACS Photonics (2020). DOI:10.1021/acsphotonics.0c00833.
2. Alison E. Rugar, Haiyu Lu, Constantin Dory, Shuo Sun, Patrick J. McQuade, Zhi-Xun Shen, Nicholas A. Melosh, Jelena Vuckovic, *Generation of Tin-Vacancy Centers in Diamond via Shallow Ion Implantation and Subsequent Diamond Overgrowth*, Nano Lett. **20**, 1614-19 (2020).
3. Constantin Dory, Dries Vercruysse, Ki Youl Yang, Neil V. Sapra, Alison E. Rugar, Shuo Sun, Daniil M. Lukin, Alexander Y. Piggott, Jingyuan L. Zhang, Marina Radulaski, Konstantinos G. Lagoudakis, Logan Su, and Jelena Vuckovic, *Inverse-Designed Diamond Photonics*, Nat. Commun. **10**, 3309 (2019).

Submitted to Peer-Reviewed Journals

1. "A Quantum Photonic Interface for Tin-Vacancy Centers in Diamond," Alison E. Rugar, Shahriar Aghaeimeibodi, Daniel Riedel, Constantin Dory, Haiyu Lu, Patrick J. McQuade, Zhi-Xun Shen, Nicholas A. Melosh, and Jelena Vuckovic, submitted to *Physical Review X*, arxiv:2102.11852 (2021)
2. "Electrical control of tin-vacancy centers in diamond," Shahriar Aghaeimeibodi, Daniel Riedel, Alison E. Rugar, Constantin Dory, and Jelena Vuckovic, submitted to *Physical Review Applied* (2021) arXiv:2103.01917

Plenary and keynote talks

1. Jelena Vuckovic, *Quantum 2020,* October 19-22 2020 [plenary]
2. Jelena Vuckovic, *OSA Advanced Photonics Conference*, Montreal, Canada, July 13-16, 2020 [plenary]
3. Jelena Vuckovic, *2019 SPIE Optics + Photonics meeting*, August 2019 [plenary].
4. Jelena Vuckovic, *10th International Conference on Metamaterials, Photonic Crystals and Plasmonics (META 2019)*, Lisbon -Portugal, July 23-26, 2019 [keynote].
5. Jelena Vuckovic, *ICOLS 2019*, Queenstown, New Zealand, July 8-12, 2019.

6. Jelena Vuckovic, a plenary presentation at the *Central European Workshop on Quantum Optics (CEWQO)*, Paderborn, Germany, June 3rd -7th, 2019 [plenary].
7. Jelena Vuckovic, *IEEE New Frontiers in Computing (NFIC) Conference,* Stanford University, May 14, 2019 [keynote].

Invited talks

At major international conferences

1. Jelena Vuckovic, "Quantum integrated photonics," *CLEO Science and Innovations*, San Jose, CA, May 2020.

2. Jelena Vuckovic, *APS March Meeting*, Denver, CO, March 2-6, 2020.

At meetings, symposia, and workshops

3. Jelena Vuckovic, "Connecting and scaling semiconductor quantum photonic systems," *Photonics for Quantum (PfQ2)*,Rochester Institute of Technology (RIT), June 2020.

4. Jelena Vuckovic, "From inverse design to implementation of practical photonics," *MRS Spring Meeting*, Phoenix, Arizona, April 13 -17, 2020.

5. Jelena Vuckovic, *Special Symposium on Quantum Information Science and Technology (QIST), Optical Fiber Communication Conference and Exhibition (OFC 2020)*, San Diego, CA, March 9-10, 2020.

6. Jelena Vuckovic, *Aspen Winter Conference on Quantum Information and Systems for Fundamental Physics*, Aspen, CO, Feb. 17-22, 2020.

7. Jelena Vuckovic, Rahul Trivedi, *Winter Colloquium on the Physics of Quantum Electronics (PQE)*, Snowbird, UT, Jan 5-10, 2020.
8. Jelena Vuckovic, Symposium on "Nanoscale and molecular assemblies: Designing matter to control energy transport" *Fall 2019 American Chemical Society Meeting*, San Diego, CA from August 25 -29, 2019.

9. Jelena Vuckovic, *SPIE Optics & Photonics conference on Quantum Nanophotonics Materials, Devices and Systems*, San Diego, CA August 11-15, 2019.

10. Jelena Vuckovic, *Quantum Symposium at the OSA Advanced Photonics Congress*, San Francisco, CA, July 29-Aug. 1, 2019.

Colloquia and seminars

Peer-reviewed conference publications

1. Alison E. Rugar, Haiyu Lu, Constantin Dory, Shuo Sun, Patrick McQuade, Zhi-Xun Shen, Nicholas Melosh, Jelena Vuckovic, *Site-controlled generation of tin-vacancy centers in*

diamond via shallow ion implantation and subsequent diamond growth, American Physics Society (APS) March Meeting 2020, Denver, CO, USA, contributed talk.

2. Alison E. Rugar, Haiyu Lu, Constantin Dory, Shuo Sun, Patrick J. McQuade, Zhi-Xun Shen, Nicholas A. Melosh, and Jelena Vuckovic, *Site-Controlled Generation of Tin-Vacancy Centers in Diamond via Shallow Ion Implantation and Diamond Overgrowth*, Conference on Lasers and Electro-Optics (CLEO) 2020, San Jose, CA, USA, contributed talk.

Detailed research report

1. Site-Controlled Generation of SnV^- Centers in Diamond via Shallow Ion Implantation and Growth

Color centers in diamond have been the focus of many recent efforts to engineer optically active solid-state spin qubits. Incorporating these color centers into photonic devices in a scalable fashion necessitates the generation of high-quality, site-controlled emitters. This requirement is particularly difficult to fulfill with color centers based on larger group-IV impurities, which are otherwise promising spin qubit candidates because of their potential to have long coherence times without a dilution refrigerator [1]. When applied to large group-IV color centers *e.g.* tin-vacancy (SnV^-) centers, conventional techniques for site-controlled color center generation falter. Ion implantation and annealing either yields SnV^- samples with messy bulk spectra [2] or can damage diamond surfaces [3], making this approach unsuitable for photonics applications.

To overcome these trade-offs, we have developed a technique, which we call shallow ion implantation and growth (SIIG). Our results have been published in [4]. The method is illustrated in Fig. 1(a). To create an array of SnV^- centers, we create an implantation mask of ~50 nm of poly(methyl methacrylate) (PMMA) patterned via electron-beam lithography. $^{120}Sn^+$ ions are then implanted at 1 keV, resulting in an ion depth of ~2 nm. After implantation, ~90 nm of diamond is grown on the chip via microwave-plasma chemical vapor deposition (MPCVD).

A photoluminescence (PL) map showing a resulting array of SnV^- centers is presented in Fig. 1(b). A PL spectrum acquired at the spot circled in red in Fig. 1(b) is presented in Fig. 1(c), displaying the signature zero-phonon lines (ZPLs) of the SnV^- center.

The SIIG method of generating SnV^- centers also produces samples with cleaner bulk spectra than those that have undergone high-energy implantation and vacuum annealing, as shown in the spectra of Fig. 1(d). Three prominent differences in the spectra have been marked with P1, P2, and P3. The peaks at P1 and P2 have been suppressed in previous studies [2] with high-pressure, high-temperature annealing. P3 is a peak that has been predicted by *ab initio* studies [1] to appear in the phonon sideband of SnV^- centers. It is notable that with SIIG we can suppress the extraneous spectral lines at P1 and P2 without the need for annealing of any kind.

The development of SIIG enables us to move towards incorporating the SnV^- center into photonic devices. Additionally, we believe that SIIG can be applied to numerous other color centers in other host materials.

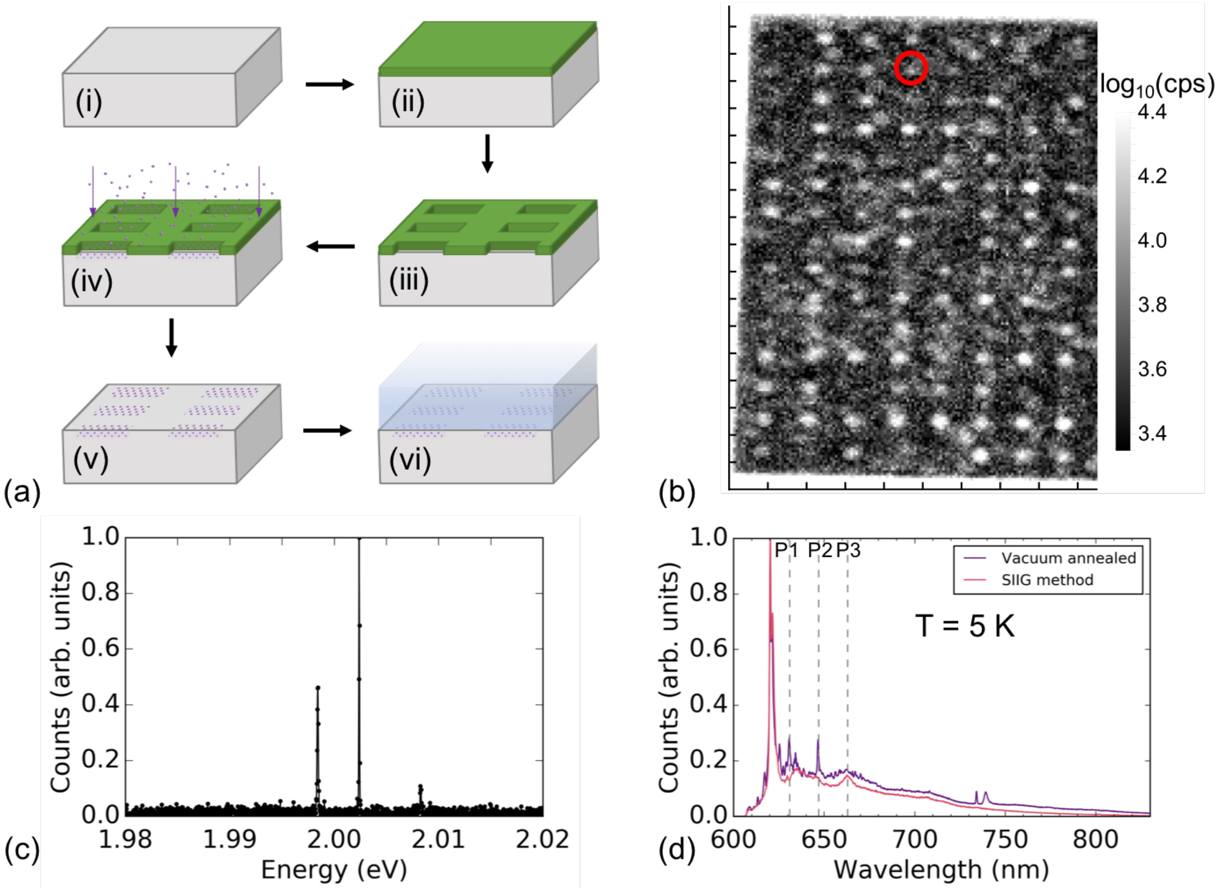

Fig. 1. *SIIG method and results. (a) Site-controlled color center generation via SIIG. (i) Starting with an electronic grade diamond chip that has been cleaned and etched, (ii) spin on PMMA. (iii) Pattern holes in PMMA. (iv) Implant* $^{120}Sn^{+}$ *ions at 1 keV. (v) Strip PMMA. (vi) Perform* H_2 *plasma clean and grow diamond via MPCVD. (b) PL map of resulting array of* SnV^- *centers. (c) PL spectrum of the spot circled in red in (b). (d) Cryogenic PL spectra of two samples prepared via different methods. P1, P2, P3 denote wavelengths at which the spectra differ significantly.*

2. Narrow-Linewidth SnV$^-$ Centers in Diamond Waveguides

The development of large-scale optical quantum information processing requires the integration of quantum emitters into photonic devices. However, despite the promising potential presented by the SnV$^-$ center in diamond, it had not been incorporated into waveguides until very recently. We recently made the first demonstration of a SnV$^-$ center coupled to a nanophotonic waveguide [5].

To this end, we combined our SIIG method for generation of the color centers [4] with advanced quasi-isotropic etching of diamond [6] for fabrication of the suspended optical waveguides. Fig. 2(a) shows the PL map of a representative device. Isolated bright spots in the middle of the waveguide correspond to SnV$^-$ centers. We terminated our waveguides with vertical couplers (VC) on both ends to have an interface for on- and off-chip coupling.

To further confirm the presence of the SnV^- centers, we performed PL spectroscopy on the sample loaded in a 1.7 K cryostat. Fig. 2(b) shows the PL spectrum collected in a configuration illustrated above the panel. We observed several distinct ZPLs around 620 nm, which indicates the presence of many color centers on the waveguide.

Finally, to fully take advantage of the on-chip waveguide, we performed a waveguide-coupled PL excitation (PLE) measurement. Here, a resonant laser with the color center is incident on one VC, while the phonon sideband emission from the emitter is collected from the VC on the other end of the device (illustrated above Fig. 2(c)). We extract the linewidth of the emitter by fitting a Lorentzian function to the PLE data in Fig. 2(c). Remarkably, we observed a very narrow linewidth of 36±2 MHz, which is comparable with lifetime-limited linewidth in SnV^- centers in bulk [7] and simple structures such as micropillars [8]. The ability to produce narrow-linewidth SnV^- in suspended waveguides enables future fabrication of large-scale photonic circuitry and quantum photonics experiments.

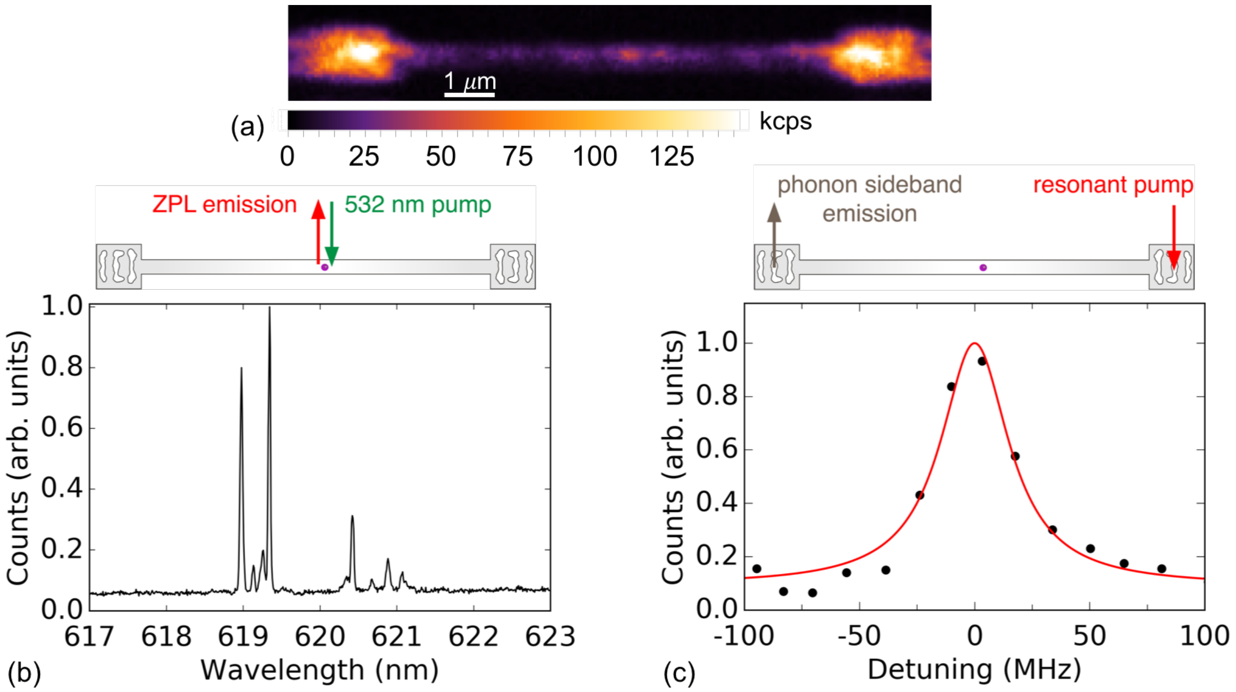

Fig. 2. *PL and PL excitation of SnV- centers in diamond waveguides. (a) PL map of a diamond waveguide with SnV- centers. (b) PL spectrum acquired on a waveguide. Several distinct SnV- ZPLs are apparent, indicating the presence of many SnV- centers in the waveguide. Excitation (532 nm) and detection were aligned to the same spot. (c) PL excitation of SnV- center in waveguide. A Lorentzian fit reveals a linewidth of 36±2 MHz. Measurement configurations illustrated schematically above corresponding plots.*

References

1. G. Thiering and A. Gali, Phys. Rev. X **8**, 021063 (2018).

2. T. Iwasaki et al., Phys. Rev. Lett. **119**, 253601 (2017).
3. I. Dobrinets, V. G. Vins, and A. Zaitsev, HPHT-Treated Diamonds, vol. 181 (Springer Series in Materials Science, Springer, Berlin, Heidelberg, 2013).
4. A. E. Rugar et al., Nano Lett. **20**, 1614-1619 (2020).
5. A. E. Rugar*, C. Dory*, S. Aghaeimeibodi* et al. arXiv:2005.10385 (2020).
6. C. Dory et al., Nat. Commun. **10**, 3309 (2019).
7. J. Görlitz et al., New J. Phys. **22**, 013048 (2020).
8. M. E. Trusheim, B. Pingault et al., Phys. Rev. Lett. **124**, 023602 (2020).

3. Purcell enhancement of SnV centers using nanophotonic cavities

An important figure of merit for incorporating SnV centers into a quantum network is the efficiency of coupling zero-photon-line (ZPL) photons into a photonic quantum link. By incorporating SnV centers into nanophotonic resonators we manage to channel more than 90% of the SnV emission into a single optical cavity mode via the relevant ZPL transition. We demonstrate a more than 10-fold enhancement of the spontaneous radiative recombination rate of individual SnV centers corresponding to a 25-fold enhancement of the ZPL transition.

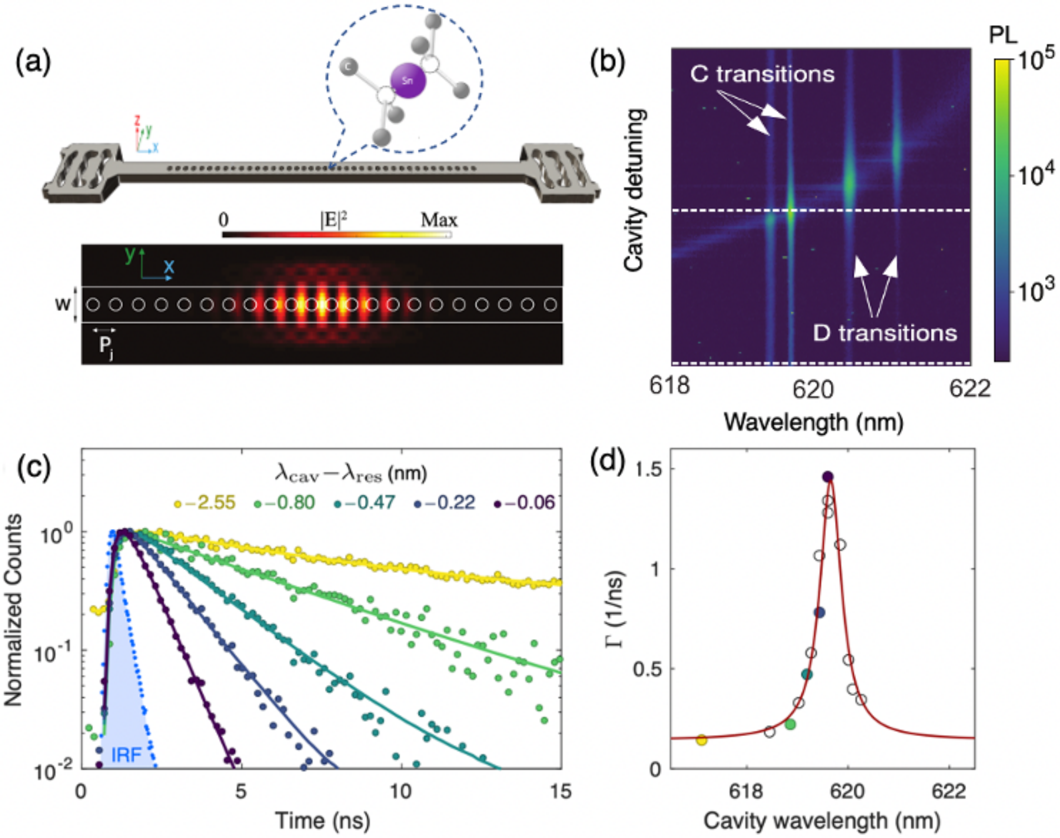

Figure 3. (a) Design and simulation of the nanobeam photonic crystal cavity. Tapering of the hole distances creates the photonic confinement. **(b)** Consecutive PL spectra acquired while gas tuning the cavity through resonance with the ZPLs of two SnV centers. **(c)** Representative lifetime measurements at different cavity wavelengths. To fit the data, we convolve a single-exponential decay with the instrument response function (IRF) of our detectors (blue). **(d)** PL recombination rates of the studied SnV center plotted as a function of cavity resonance wavelength. Filled circles correspond to lifetime data of the same color shown in (c).

Our platform is based on a one-dimensional photonic crystal nanobeam cavity fabricated in diamond. Here, a strong confinement of photons is achieved by etching an array of circular holes into the nanobeam, the spacings of which are tapered towards the center of the device (Fig. 3a). We use high-quality electronic grade diamond as a starting material and employ the SIIG method to create a δ-doped layer of high-quality SnV centers ~90nm below the diamond surface corresponding to half of the desired device thickness. Next, we fabricate, in parallel, a matrix of hundreds of nanobeam cavities via the quasi-isotropic undercut method. By performing a broadband transmission measurement we characterize the resonance frequency and quality factor of our devices. Using non-resonant excitation at the center of the nanocavities, we verify the presence of SnV center by recording photoluminescence (PL) spectra. We employ argon gas adsorption to tune the resonance frequency of our devices and while measuring the PL and find a 40-fold enhancement of the intensity of the C- and D-transitions (Fig. 3b). We isolate the emission into the C-transition of a single SnV center using a monochromator and measure the PL decay rate by exciting the system with short non-resonant pulses. Fig. 3c displays such lifetime measurements for different detunings of the cavity resonance from the C-transition. We find a more than 10-fold reduction of the PL lifetime from ~7ns to ~0.7ns. Upon tuning the cavity resonance and recording the radiative lifetime we reconstruct the expected Lorentzian-shaped wavelength dependence of the radiative Purcell enhancement (Fig. 3d). Extracting all relevant parameters from a fit to these data, we infer that more than 90% of the SnV emission is channeled into a single cavity mode via the relevant ZPL transition.

Our results constitute the state-of-the-art for coupling SnV centers to photonic resonators and confirm the feasibility of implementing a scalable nanophotonic platform for SnV centers in diamond. We anticipate the potential for reaching the strong coupling regime in this system, which is essential for many applications in quantum information and quantum optics.

References

1. "A Quantum Photonic Interface for Tin-Vacancy Centers in Diamond," Alison E. Rugar, Shahriar Aghaeimeibodi, Daniel Riedel, Constantin Dory, Haiyu Lu, Patrick J. McQuade, Zhi-Xun Shen, Nicholas A. Melosh, and Jelena Vuckovic, submitted to *Physical Review X*, arxiv:2102.11852 (2021)

4. DC Stark tuning of SnV centers

Photonic quantum networks require quantum nodes that emit indistinguishable single photons. A major challenge for solid-state emitters, including SnV color centers, is that each emitter experiences a slightly different strain environment, leading to an inhomogeneous broadening in their transition frequencies. Improving growth conditions in order to reduce strain in the crystal lattice can shrink this spread of transition frequencies significantly. However, nanofabrication can induce additional strain on the emitter. Therefore, establishing mechanisms to fine-tune the transition frequency of solid-state emitters is essential for the realization of scalable quantum networks. Although strain and Raman tuning have been investigated as promising techniques to overcome the spectral mismatch between distinct group-IV color centers, more localized techniques that maintain the emission intensity of the emitter are needed. We investigate the electric field susceptibility of SnV centers in diamond. We demonstrated reversible tuning of the transition wavelength by more than 1.7 GHz, which is ~57 times the natural linewidth. A scanning electron microscope image of the fabricated diamond structures and metal electrodes is shown in Fig. 4(a).

We perform a photoluminescence excitation (PLE) measurement on one of SnV centers located between the electrodes to characterize its resonant frequency and linewidth. Fig. 4(b) shows consecutive PLE scans of the color center as we vary the applied voltage. Repeatable tuning of the emission frequency confirms that there is no damage to the SnV even at extremely high electric fields. To gain a better understanding of the origin of the shift for single SnV centers, we fit the PLE data to a Lorentzian function to extract the shift, linewidth, and the intensity of the signal as we vary the electric field. Fig. 4(c) shows the extracted shift of the resonance frequency of the SnV center as a function of the applied electric field. We observe a predominantly quadratic dependence which is consistent with inversion symmetric emitters. Finally, we repeat the above measurement for several SnV centers. Interestingly, some emitters show a predominantly linear dependence of transition frequencies on applied electric field (Fig. 4(d)) which could be explained by strain-induced symmetry breaking. In addition to contributing to a deeper understanding of the basic properties of SnV centers, this work paves the way for multi-emitter experiments based on group-IV color centers harnessing Stark shift tuning.

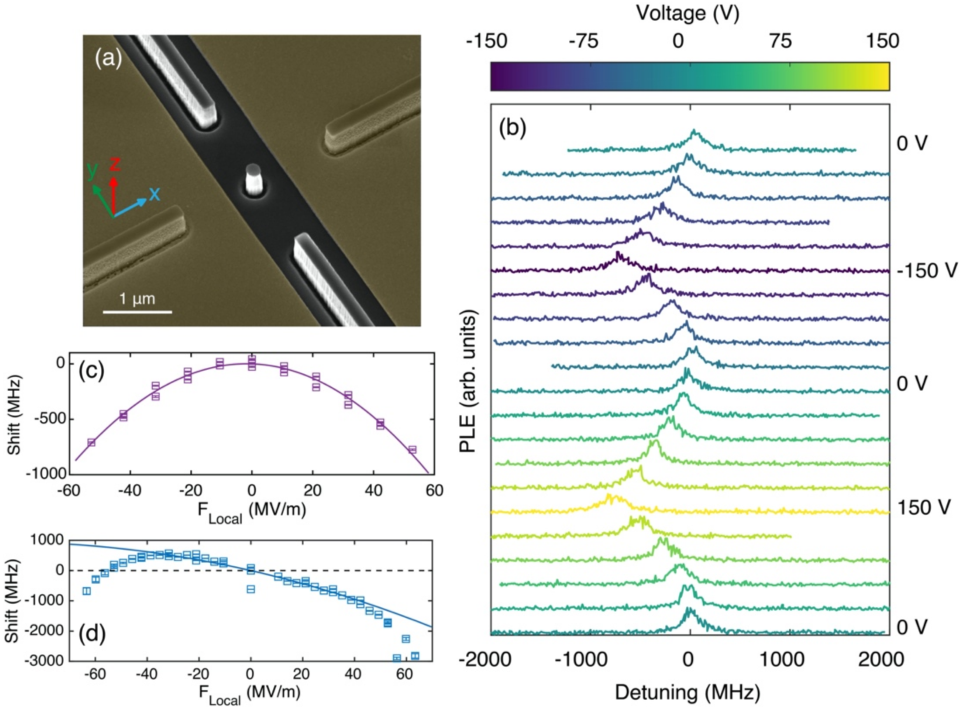

Fig. 4. Stark tuning SnV centers in diamond. **(a)** False color scanning electron microscope image of the fabricated device with the metal electrodes highlighted by the gold color. **(b)** Voltage-dependent photoluminescence excitation measurement. **(c)** Extracted transition frequency shifts from Lorentzian fitting to the data in (b) exhibiting a predominantly quadratic behavior. **(d)** Extracted frequency shift for another SnV center showing a predominantly linear shift.

References

1. "Electrical control of tin-vacancy centers in diamond," Shahriar Aghaeimeibodi, Daniel Riedel, Alison E. Rugar, Constantin Dory, and Jelena Vuckovic, submitted to *Physical Review Applied* (2021) arXiv:2103.01917