Samuel G. Carter

Research Physicist

Laboratory for Physical Sciences
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EDUCATION

1999-2004 **PhD Physics**, *University of California, Santa Barbara*
Dissertation: *Terahertz electro-optic effects in (In)GaAs quantum wells*
Advisor: Mark Sherwin

1994-1999 **BS Physics, BA Chemistry**, *Brigham Young University, Provo, UT*

PROFESSIONAL EXPERIENCE

6/2022-present **Research Lead,** *Laboratory for Physical Sciences*, College Park, MD

- Leading research project on spin qubits in SiGe electrically-defined quantum dots for quantum information processing
- Leading research project on quantum sensing with defects in SiC

10/2007-6/2022 **Research Physicist,** *US Naval Research Laboratory*, Washington, DC

Spectroscopy and coherent control of solid-state quantum systems: semiconductor quantum dots and defects in solids

- Led internal and external programs on quantum sensing, entangled photon generation, and defect-based magnetometry
- Demonstrated coupling of quantum dot spins to mechanical and optical resonators
- Performed first high-resolution spectroscopy of single silicon vacancies in SiC
- Performed single and two-qubit gates on two spins in coupled quantum dots

2005-2007 **NRC Postdoctoral Research Associate**, *NIST/JILA*, Boulder, CO
Advisor: Steve Cundiff
Ultrafast spectroscopy of spin and exciton dynamics in quantum wells

- Demonstrated the first ground state spin rotations in quantum wells

2000-2004 **Graduate Student Researcher**, *Physics Department, University of California, Santa Barbara*
Advisor: Mark Sherwin
Optical spectroscopy and nonlinear optics of semiconductor quantum wells driven by intense terahertz radiation

AWARDS AND HONORS

2021 Alan Berman Research Publication Award

2018 Alan Berman Research Publication Award
2014 Sigma Xi Young Investigator Award
2013 Alan Berman Research Publication Award
2005-2007 National Research Council Fellowship
2000 John Cardy Award for graduate academic performance

RESEARCH SKILLS

- Ultrafast optical spectroscopy
- High resolution optical spectroscopy
- Optical characterization of photonic crystals and mechanical resonators
- Electrical measurements of quantum devices
- Cryogenics, superconducting magnets, electromagnets
- Confocal microscopy with cryogenic systems
- Quantum optics measurements: Hanbury Brown—Twiss, Hong-Ou-Mandel
- Optically detected magnetic resonance, including Ramsey fringes and spin echo
- Modeling quantum optics
- Labview, Python, Matlab, QuTIP

PUBLICATIONS, PRESENTATIONS, AND PATENTS

Author and/or co-author of 49 published articles and chapters in scientific journals and books

h-index: 24 (from Google Scholar)

Journal articles

1. I. Lekavicius, **S. G. Carter**, D. J. Pennachio, S. White, J. R. Hazjus, A. P. Purdy, D. K. Gaskill, A. L. Yeats, and R. L. Myers-Ward, *Magnetometry Based on Silicon-Vacancy Centers in Isotopically Purified 4H-SiC*, Phys. Rev. Applied **19**, 044086 (2023).
2. M. A. Stevens, W. McKenzie, G. Baumgartner, J. Q. Grim, **S. G. Carter**, and A. S. Bracker, *InAs quantum emitters at telecommunication wavelengths grown by droplet epitaxy*, J. Vac. Sci. Technol. A **41**, 032703 (2023).
3. D. Farfurnik, H. Singh, Z. Luo, A. S. Bracker, **S. G. Carter**, R. M. Pettit, and E. Waks, *All-Optical Noise Spectroscopy of a Solid-State Spin*, Nano Lett. **23**, 1781-1786 (2023).
4. H. Singh, D. Farfurnik, Z. Luo, A. S. Bracker, **S. G. Carter**, and E. Waks, *Optical Transparency Induced by a Largely Purcell Enhanced Quantum Dot in a Polarization-Degenerate Cavity*, Nano Lett. **22**, 7959-7964 (2022).
5. J. Q. Grim, I. Welland, **S. G. Carter**, A. S. Bracker, A. Yeats, C. S. Kim, M. Kim, K. Tran, I. Vurgaftman, and T. L. Reinecke, *Scattering laser light from two resonant quantum dots in a photonic crystal waveguide*, Phys. Rev. B **106**, L081403 (2022).
6. K. X. Tran, A. S. Bracker, M. K. Yakes, J. Q. Grim, and **S. G. Carter**, *Enhanced Spin Coherence of a Self-Assembled Quantum Dot Molecule at the Optimal Electrical Bias*, Phys. Rev. Lett **129**, 027403 (2022).

7. I. Lekavicius, R.L. Myers-Ward, D.J. Pennachio, J.R. Hajzus, D.K. Gaskill, A.P. Purdy, A.L. Yeats, P.G. Brereton, E.R. Glaser, T.L. Reinecke, and **S.G. Carter**, *Orders of Magnitude Improvement in Coherence of Silicon-Vacancy Ensembles in Isotopically Purified 4H-SiC,* PRX Quantum 3, 010343 (2022).
8. **S. G. Carter**, S. C. Badescu, A. S. Bracker, M. K. Yakes, K. X. Tran, J. Q. Grim, and D. Gammon, *Coherent population trapping combined with cycling transitions for quantum dot hole spins using triplet trion states*, Phys. Rev. Lett. **126**, 107401 (2021).
9. S. P. Pavunny, A. L. Yeats, H. B. Banks, E. Bielejec, R. L. Myers-Ward, M. T. DeJarld, A. S. Bracker, D. K. Gaskill and **S. G. Carter**, *Arrays of Si vacancies in 4H-SiC produced by focused Li ion beam implantation*, Sci. Rep. **11**, 3561 (2021).
10. P. Kumar, C. Jennings, M. Scheibner, A. S. Bracker, **S. G. Carter**, and D. Gammon, *Spectral broadening of optical transitions at tunneling resonances in InAs/GaAs coupled quantum dot pairs*, Phys. Rev. B **102**, 085423 (2020).
11. P. G. Brereton, D. Puent, J. Vanhoy, E. R. Glaser, and **S. G. Carter**, *Spin coherence as a function of depth for high-density ensembles of silicon vacancies in proton-irradiated 4H–SiC*, Solid State Commun. 320, 114014 (2020).
12. D. M. Photiadis, M. K. Zalalutdinov, A. S. Bracker, **S. G. Carter**, D. Gammon, and B. H. Houston, *Photoexcited elastic waves in free-standing GaAs films*, Phys. Rev. B **101**, 245304 (2020).
13. J. J. Fonseca, A. L. Yeats, B. Blue, M. K. Zalalutdinov, T. Brintlinger, B. S. Simpkins, D. C. Ratchford, J. C. Culbertson, J. Q. Grim, **S. G. Carter**, M. Ishigami, R. M. Stroud, C. D. Cress, and J. T. Robinson, *Enabling remote quantum emission in 2D semiconductors via porous metallic networks*, Nat. Commun. **11**, 5 (2020).
14. S. P. Pavunny, R. L. Myers-Ward, K. M. Daniels, W. Shi, K. Sridhara, M. T. DeJarld, A. K. Boyd, F. J. Kub, P. A. Kohl, **S. G. Carter**, and D. K. Gaskill, *On the doping concentration dependence and dopant selectivity of photogenerated carrier assisted etching of 4H-SiC epilayers*, Electrochimica Acta **323**, 134778 (2019).
15. B. Lee, B. C. Pursley, **S. G. Carter**, S. E. Economou, M. K. Yakes, J. Q. Grim, A. S. Bracker, and D. Gammon, *Spin-dependent quantum optics in a quantum dot molecule*, Phys. Rev. B **100**, 125438 (2019).
16. Z. Luo, S. Sun, A. Karasahin, A. S. Bracker, **S. G. Carter**, M. K. Yakes, D. Gammon, E. Waks, *A Spin–Photon Interface Using Charge-Tunable Quantum Dots Strongly Coupled to a Cavity*, Nano Lett. **19**, 7072-7077 (2019).
17. **S. G. Carter**, A. S. Bracker, M. K. Yakes, M. K. Zalalutdinov, M. Kim, C. S. Kim, B. Lee, and D. Gammon, *Tunable coupling of a double quantum dot spin system to a mechanical resonator,* Nano Lett. **19**, 6166-6172 (2019).
18. J. Q. Grim, A. S. Bracker, M. Zalalutdinov, **S. G. Carter**, A. C. Kozen, M. Kim, C. S. Kim, J. T. Mlack, M. Yakes, B. Lee, D. Gammon, *Scalable in operando strain tuning in nanophotonic waveguides enabling three- quantum-dot superradiance*, Nature Materials **18**, 963–969 (2019).
19. P. M. Vora, A. S. Bracker, **S. G. Carter**, M. Kim, C. S. Kim, and D. Gammon, *Strong coupling of a quantum dot molecule to a photonic crystal cavity*, Phys. Rev. B **99**, 165420 (2019).
20. H. B. Banks, O. O. Soykal, R. L. Myers-Ward, D. K. Gaskill, T. L. Reinecke, and **S. G. Carter**, *Resonant optical spin initialization and readout of single silicon vacancies in 4H-SiC*, Phys. Rev. Applied **11**, 024013 (2019).
21. **S. G. Carter**, A. S. Bracker, G. W. Bryant, M. Kim, C. S. Kim, M. K. Zalalutdinov, M. K. Yakes, C. Czarnocki, J. Casara, M. Scheibner, and D. Gammon, *Spin-mechanical coupling of an InAs quantum dot embedded in a mechanical resonator*, Phys. Rev. Lett. **121**, 246801 (2018).
22. B.C. Pursley, **S.G. Carter**, M.K. Yakes, A.S. Bracker, and D. Gammon, *Picosecond pulse shaping of single photons using quantum dots*, Nat. Commun. **9**, 115 (2018).

23. **S. G. Carter**, A. S. Bracker, M. K. Yakes, M. K. Zalalutdinov, M. Kim, C. S. Kim, C. Czarnocki, M. Scheibner, and D. Gammon, *Sensing flexural motion of a photonic crystal membrane with InGaAs quantum dots*, Appl. Phys. Lett. **111**, 183101 (2017).
24. J. S. Embley, J. S. Colton, K. G. Miller, M. A. Morris, M. Meehan, S. L. Crossen, B. D. Weaver, E. R. Glaser, and **S. G. Carter**, *Electron spin coherence of silicon vacancies in proton- irradiated 4H-SiC*, Phys. Rev. B **95**, 045206 (2017).
25. L. Yang, **S. G. Carter**, A. S. Bracker, M. K. Yakes, M. Kim, C. S. Kim, P. M. Vora, and D. Gammon, *Optical spectroscopy of site-controlled quantum dots in a Schottky diode*, Appl. Phys. Lett. **108**, 233102 (2016).
26. **S. G. Carter**, O. O. Soykal, Pratibha Dev, Sophia E. Economou, and E. R. Glaser, *Spin coherence and echo modulation of the silicon vacancy in 4H-SiC at room temperature*, Phys. Rev. B **92**, 161202(R) (2015).
27. P. M. Vora, A. S. Bracker, **S. G. Carter**, T. M. Sweeney, M. Kim, C. S. Kim, L. Yang, P. G. Brereton, S. E. Economou, and D. Gammon, *Spin-cavity interactions between a quantum dot molecule and a photonic crystal cavity*, Nature Comm. **6**, 1-9 (2015).
28. T. M. Sweeney, **S. G. Carter**, A. S. Bracker, M. Kim, C. S. Kim, L. Yang, P. M. Vora, P. G. Brereton, E. R. Cleveland, D. Gammon, *Cavity-stimulated Raman emission from a single quantum dot spin*, Nature Photon. **8**, 442-447 (2014).
29. **S. G. Carter**, Sophia E. Economou, A. Greilich, Edwin Barnes, T. Sweeney, A. S. Bracker, and D. Gammon, *Strong hyperfine-induced modulation of an optically driven hole spin in an InAs quantum dot*, Phys. Rev. B **89**, 075316 (2014).
30. M. K. Yakes, L. Yang, A. S. Bracker, T. M. Sweeney, P. G. Brereton, M. Kim, C. S. Kim, P. M. Vora, D. Park, **S. G. Carter**, and D. Gammon, *Leveraging Crystal Anisotropy for Deterministic Growth of InAs Quantum Dots with Narrow Optical Linewidths*, Nano Lett. **13, 4870-4875** (2013).
31. **S. G. Carter**, T. M. Sweeney, M. Kim, C. S. Kim, D. Solenov, S. E. Economou, T. L. Reinecke, L. Yang, A. S. Bracker, and D. Gammon, *Quantum control of a spin qubit coupled to a photonic crystal cavity*, Nature Photon. **7**, 329-334 (2013).
32. A. Greilich, **S. G. Carter**, D. Kim, A. S. Bracker, and D. Gammon, *Optical control of one and two hole spins in interacting quantum dots*, Nature Photon. **5**, 702-8 (2011).
33. **S. G. Carter**, Sophia E. Economou, A. Shabaev, and A. S. Bracker, *Controlling the nuclear polarization in quantum dots using optical pulse shape with a modest bandwidth*, Phys. Rev. B **83**, 115325 (2011).
34. D. Kim, **S. G. Carter**, A. Greilich, A. S. Bracker, and D. Gammon, *Ultrafast optical control of entanglement between two quantum-dot spins*, Nature Physics **7**, 223 (2011).
35. Z. Chen, **S. G. Carter**, R. Bratschitsch, and S. T. Cundiff, *Optical excitation and control of electron spins in semiconductor quantum wells*, Physica E **42**, 1803 (2010).
36. **S. G. Carter**, Ş. C. Bădescu, and A. S. Bracker, *Electron spin polarization and detection in InAs quantum dots through p-shell trions*, Phys. Rev. B **81**, 045305 (2010).
37. **S. G. Carter**, A. Shabaev, Sophia E. Economou, T. A. Kennedy, A. S. Bracker, and T. L. Reinecke, *Directing Nuclear Spin Flips in InAs Quantum Dots Using Detuned Optical Pulse Trains*, Phys. Rev. Lett. **102**, 167403 (2009).
38. **S. G. Carter**, Z. Chen, S. T. Cundiff, *Ultrafast below-resonance Raman rotation of electron spins in GaAs quantum wells*, Phys. Rev. B **76**, 201308(R) (2007).
39. **S. G. Carter**, Z. Chen, S. T. Cundiff, *Echo Peak Shift Spectroscopy of Non-Markovian Exciton Dynamics in Quantum Wells*, Phys. Rev. B **76**, 121303(R) (2007).

40. Z. Chen, R. Bratschitsch, **S. G. Carter**, S. T. Cundiff, D. R. Yakovlev, G. Karczewski, T. Wojtowicz, and J. Kossut, *Electron spin polarization through interactions between excitons, trions, and the two-dimensional electron gas*, Phys. Rev. B **75**, 115320 (2007).
41. Z. Chen, **S. G. Carter**, R. Bratschitsch, P. Dawson, and S. T. Cundiff, *Influence of Disorder on Electron Spin Dynamics in Semiconductor Quantum Wells*, *Nature Physics* **3**, 265 (2007).
42. **S. G. Carter**, Z. Chen, and S. T. Cundiff, O*ptical measurement and control of spin diffusion in n-doped GaAs quantum wells*, *Phys. Rev. Lett.* **97**, 136602 (2006).
43. **S. G. Carter**, V. Birkedal, C. S. Wang, L. A. Coldren, A. V. Maslov, D. S. Citrin, and M. S. Sherwin, *Quantum Coherence in an Optical Modulator*, Science **310**, 651 (2005).
44. **S. G. Carter**, V. Ciulin, M. Hanson, A. S. Huntington, C. S. Wang, A. C. Gossard, L. A. Coldren, and M. S. Sherwin*, Terahertz-optical mixing in undoped and doped GaAs quantum wells: From excitonic to electronic intersubband transitions*, Phys. Rev. B **72**, 155309 (2005).
45. V. Ciulin, **S. G. Carter**, M. S. Sherwin, A. Huntington, and L. A. Coldren, *THz optical mixing in biased GaAs single quantum wells*, Phys. Rev. B **70**, 115312 (2004).
46. **S. G. Carter**, V. Ciulin, M. S. Sherwin, M. Hanson, A. Huntington, L. A. Coldren, and A. C. Gossard, *THz electro-optic wavelength conversion in GaAs quantum wells: Improved efficiency and room-temperature operation*, *Appl. Phys. Lett*. **84**, 840 (2004).
47. M. Y. Su, **S. G. Carter**, M. S. Sherwin, A. Huntington, and L.. A. Coldren, *Strong-field terahertz optical mixing in excitons*, Phys Rev. B **67**, 125307 (2003).
48. M. Y. Su, **S. G. Carter**, M. S. Sherwin, A. Huntington, and L. A. Coldren, *Voltage-controlled wavelength conversion by terahertz electro-optic modulation in double quantum wells*, Appl. Phys. Lett. **81**, 1564 (2002).

Book Chapters

1. **S. G. Carter**, J. Cerne, and M. S. Sherwin, "Optical Response of Semiconductor Nanostructures in Terahertz Fields Generated by Electrostatic Free-Electron Lasers," *Terahertz Spectroscopy: Principles and Applications*, Editor Susan L. Dexheimer, CRC Press, 2008.

Invited Presentations

1. "Spin and optical properties of the silicon vacancy in 4H-SiC for quantum science and technology," 242nd Meeting of the Electrochemical Society, Oct 9-13, 2022, Atlanta, GA.
2. "Spin coherence and optical properties of the silicon vacancy in 4H-SiC," Materials Research Society 2021 Fall Meeting (Virtual), Dec 6-8, 2021.
3. "Epitaxial Quantum Dots for Quantum Science and Technology," American Vacuum Society 67 Virtual Symposium, Oct 25-28, 2021.
4. "Spins in InAs quantum dots: qubits, sensors, and photon sources," Quantum Information Science Workshop at Argonne National Lab, Sept 23-24, 2019 Lemont, IL.
5. "Optical Properties of Single Silicon Vacancies in 4H-SiC", presented at SiC quantum spintronics: towards quantum devices in a technological material, 5-6 Nov 2018, Buckinghamshire, UK
6. "Picosecond pulse shaping of single photons using quantum dots," presented at SPIE Defense + Commercial Sensing, 15-19 April 2018 Orlando, FL.
7. "Optical control of spins and photons in quantum dots", presented at OSA Incubator on Integrated Semiconductor Quantum Photonic Devices, 18-20 June 2017 Washington, DC.
8. "Spin Coherence and Optical Properties of the Si Vacancy in SiC," Materials Research Society Spring Meeting, 4/20/17, Phoenix, AZ.

9. “Quantum sensing of mechanical motion with a single InAs quantum dot,” GOMACTech, 3/22/2017, Reno, NV.
10. "Cavity-enhanced Raman spin flip emission from single and coupled quantum dots,” International Workshop on Nano-spin Conversion Science and Quantum Spin Dynamics, 10/2016, Tokyo, Japan.
11. “Coupling Spins in Quantum Dots to Photonic Crystal Cavities,” Frontiers in Optics and Laser Science Conference, 10/22/14, Tucson, AZ.
12. “Optical control and coherence of electron or hole spins in coupled quantum dots,” March Meeting of the American Physical Society, 3/22/13, Baltimore, MD.
13. **“**Ultrafast optical gates with electron or hole spin qubits in quantum dots,” 11th International Workshop on Nonlinear Optics and Excitation Kinetics in Semiconductors, 9/24/2012, Stuttgart, Germany.
14. “Ultrafast optical two-qubit gates with electrons or holes,” 7th International Conference on Quantum Dots, 5/18/2012, Santa Fe, NM.
15. “Ultrafast optical control of interacting spins in coupled quantum dots,” SPIE Photonics West: Ultrafast Phenomena and Nanophotonics XVI, 1/22/2012, San Francisco, California.
16. “Ultrafast Optical Entanglement Control between two Quantum Dot Spins,” Conference on Lasers and Electro-Optics: Quantum Electronics and Laser Science Conference, 5/2/2011, Baltimore, Maryland.
17. Ultrafast optical entanglement control of two electron spins in separate quantum dots,” International Conference on the Physics of Semiconductors, 7/30/2010, Seoul, South Korea.
18. “Ultrafast optical control of electron spins in quantum wells and quantum dots,” SPIE Photonics West: Ultrafast Phenomena in Semiconductors and Nanostructure Materials XIV, 1/25/2010, San Francisco, California.

Seminars and Colloquia

1. “Spins in semiconductors for quantum information science,” Colloquium at George Mason University, Department of Physics and Astronomy, Feb 23, 2024, Fairfax, VA.
2. “Spins in semiconductors for quantum information science,” Colloquium at West Virginia University, Department of Physics and Astronomy, Jan 31, 2024, Morgantown, WV.
3. “Quantum Sensing with Solid State Spin Systems,” Seminar at the Laboratory for Physical Science Sciences, Feb 13 2021, College Park, MD.
4. “Quantum Sensing with Solid State Spin Systems,” Colloquium at US Naval Academy, Nov 20 2019, Annapolis, MD.
5. "Spins in InAs quantum dots: qubits, sensors, and photon sources," Seminar at Virginia Tech, February 11, 2019, Blacksburg, VA.
6. "Spins in InAs quantum dots: qubits, sensors, and photon sources," Seminar at Joint Quantum Institute, University of Maryland, December 10, 2018 College Park, MD.
7. "Spin Coherence and Optical Properties of the Si Vacancy in SiC," Seminar at Johns Hopkins University Applied Physics Laboratory, 16 August 2018 Laurel, MD.
8. “Spins in InAs quantum dots: qubits, sensors, and photon sources,” UC Merced Physics Department Colloquium, March 24 2017, Merced, CA.
9. “Semiconductor Quantum Dots for Quantum Information,” Naval Research Lab/University of Maryland Quantum Information Seminar Series, Jan 23 2015, College Park, MD.
10. “Semiconductor Quantum Dots for Quantum Information,” Brigham Young University Colloquium, Nov 5 2014, Provo, UT.

11. **“**Ultrafast optical gates with spin qubits in quantum dots,” Quantum information monthly seminar at the Army Research Laboratory, Feb 19 2013, Adelphi, MD.
12. “Ultrafast spin and exciton dynamics in quantum wells,” Center for Integrated Nanotechnologies, June 26 2007, Los Alamos, NM.
13. “Terahertz-optical spectroscopy of semiconductors: from “atomic” physics to terahertz optoelectronics,” Naval Research Laboratory, June 7 2007, Washington, DC.
14. “Ultrafast measurements of spin and exciton dynamics in semiconductors,” Lawrence Berkeley National Laboratory, March 1 2007, Berkeley, California.
15. “Terahertz-optical spectroscopy of semiconductors: from ‘atomic’ physics to terahertz optoelectronics,” University of Pittsburgh, Feb 12 2007, Pittsburgh, PA.
16. “Terahertz-optical spectroscopy of semiconductors: from ‘atomic’ physics to terahertz optoelectronics,” Georgia Institute of Technology, Feb 7 2007, Atlanta, GA.
17. “Terahertz-optical spectroscopy of semiconductors: from ‘atomic’ physics to terahertz optoelectronics,” Iowa State University, Jan 22 2007, Ames, Iowa.
18. “Four-wave-mixing measurements of spin coherence and optical coherence in GaAs quantum wells,” Seminar at the National High Magnetic Field Lab, June 23 2006, Tallahassee, FL.
19. “Optical properties of quantum wells driven by a strong terahertz electric field,” Brigham Young University Colloquium, Feb 22 2006, Provo, UT.

Patents

1. O. Soykal, T. L. Reinecke, **S. G. Carter**, “Quantum Metrology and Quantum Memory using Defect States with Spin-3/2 or Higher Half-Spin Multiplets,” U.S. Patent 10,762,954, Issued Sep 1, 2020; U.S. Patent 10,734,069, Issued Aug 4, 2020; U.S. Patent 10,529,416, Issued Jan 7, 2020.
2. O. Nayfeh, A. L. De Escobar, B. Liu, P. Sims, **S. Carter**, D. K. Gaskill, T. Reinecke, “Formation fo Field-Tunable SiC Defect Qubits/Quantum Memory with Optically Transparent Electrodes and SiO Surface Passivation,” U.S. Patent 10,262,871, issued April 16, 2019.
3. J. Q. Grim, A. S. Bracker, **S. G. Carter**, D. G. Gammon, "Strain Tuning Individual Quantum Dot Emission Frequencies with Local Phase Transitions" US Patent number US 11,150,495 B2, issued Oct 19, 2021.
4. J. Q. Grim, **S. G. Carter**, A. S. Bracker, D. G. Gammon, "Deterministic Frequency Tuning of Quantum Dots in Photonic Crystal Membranes Using Micro-Laser Processing," US Patent No. 10,921,519, Issued Feb 16, 2021.
5. D. Gammon, **S. Carter**, A. S. Bracker, P. Vora, “Single photon source based on a quantum dot molecule in an optical cavity,” US Patent number US9619754B2 issued : April 11, 2017