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Appendix C

Glossary of Terms

AFM: atomic force microscopy

APD: avalanche photodiode

CW: continuous-wavelength

He: Helium

CaSe: Cadmium Selenide

CQED: Cavity quantum electrodynamics

CCD: charge-coupled device

DBR: distributed Bragg reflector

FWHM: Full-Width-Half-Maximum

GaAs: Gallium Arsenide

He: Helium

HeNe: Helium-Neon

HF: Hydrofluoric acid

HG: Hermite-Gaussian

HH: heavy-hole

HV: high vacuum

InAs: Indium Arsenide

InP: Indium Phosphide

ICPRIE: inductively coupled plasma reactive ion etching

JCM: Jaynes-Cummings Model

LH: light-hole

MBE: molecular beam epitaxy

NA: numerical aperture
OD: optical density
OFHC: Oxygen-free high thermal conductivity
PC: photonic crystal
PD: photodiode
PEEK: Polyether ether ketone
PL: photoluminescence spectroscopy
RWA: rotating wave approximation
SE: spontaneous emission
SEM: scanning electron microscope
SiGe: silicon-germanium
TRIM: Transport of Ions in Matter
QD: Quantum Dot
QED: Quantum Electro Dynamics
UHV: ultra-high vacuum
VCSEL: vertical-cavity surface-emitting laser
WL: wetting layer
ZnSe: Zinc selenide

Bibliography

- [1] D. Leonard, M. Krishnamurthy, C. M. Reaves, S. P. Denbaars, and P. M. Petroff, *Direct formation of quantum-sized dots from uniform coherent islands of InGaAs on GaAs surfaces*, Appl. Phys. Lett. **63**, 3203 (1993).
- [2] H. Drexler, D. Leonard, W. Hansen, J. P. Kotthaus, and P. M. Petroff, *Spectroscopy of Quantum Levels in Charge-Tunable InGaAs Quantum Dots*, Phys. Rev. Lett. **73**, 2252 (1994).
- [3] G. Medeiros-Ribeiro, D. Leonard, and P. M. Petroff, *Electron and hole energy levels in InAs self-assembled quantum dots*, Appl. Phys. Lett. **66**, 1767 (1995).
- [4] T. Yoshie, A. Scherer, J. Hendrickson, G. Khitrova, H. Gibbs, G. Rupper, C. Ell, O. Shchekin, and D. Deppe, *Vacuum Rabi splitting with a single quantum dot in a photonic crystal nanocavity*, Nature **432**, 200 – 203 (2004).
- [5] J. P. Reithmaier, G. Sek, A. Löffler, C. Hofmann, S. Kuhn, S. Reitzenstein, L. V. Keldysh, V. D. Kulakovskii, T. L. Reinecke, and A. Forchel, *Strong coupling in a single quantum dot-semiconductor microcavity system*, Nature **432**, 197 (2004).
- [6] T. Lundstrom, W. Schoenfeld, H. Lee, and P. M. Petroff, *Exciton Storage in Semiconductor Self-Assembled Quantum Dots*, Science **286**, 2312 (1999).
- [7] M. Kroutvar, Y. Ducommun, D. Heiss, M. Bichler, D. Schuh, G. Abstreiter, and J. J. Finley, *Optically programmable electron spin memory using semiconductor quantum dots*, Nature **432**, 81 (2004).
- [8] A. Grelich, D. R. Yakovlev, A. Shabaev, A. L. Efros, I. A. Yugova, R. Oulton, V. Stavarache, D. Reuter, A. Wieck, and M. Bayer, *Mode Locking of Electron Spin Coherences in Singly Charged Quantum Dots*, Science **313**, 341 (2006).

- [9] M. Atatüre, J. Dreiser, A. Badolato, A. Högele, K. Karrai, and A. Imamoglu, *Quantum-Dot Spin-State Preparation with Near-Unity Fidelity*, *Science* **312**, 551 (2006).
- [10] J. R. Petta, A. C. Johnson, J. M. Taylor, E. A. Laird, A. Yacoby, M. D. Lukin, C. M. Marcus, M. P. Hanson, and A. C. Gossard, *Coherent Manipulation of Coupled Electron Spins in Semiconductor Quantum Dots*, *Science* **309**, 2180 (2005).
- [11] B. D. Gerardot, S. Strauf, M. J. A. de Dood, A. M. Bychkov, A. Badolato, K. Hennessy, E. L. Hu, D. Bouwmeester, and P. M. Petroff, *Photon Statistics from Coupled Quantum Dots*, *Phys. Rev. Lett.* **95**, 137403 (2005).
- [12] H. J. Krenner, M. Sabathil, E. C. Clark, A. Kress, D. Schuh, M. Bichler, G. Abstreiter, and J. J. Finley, *Direct Observation of Controlled Coupling in an Individual Quantum Dot Molecule*, *Phys. Rev. Lett.* **94**, 057402 (2005).
- [13] H. J. Krenner, E. C. Clark, T. Nakaoka, M. Bichler, C. Scheurer, G. Abstreiter, and J. J. Finley, *Optically Probing Spin and Charge Interactions in a Tunable Artificial Molecule*, *Phys. Rev. Lett.* **97**, 076403 (2006).
- [14] T. H. Stievater, X. Li, D. G. Steel, D. Gammon, D. S. Katzer, D. Park, C. Piermarocchi, and L. J. Sham, *Rabi Oscillations of Excitons in Single Quantum Dots*, *Phys. Rev. Lett.* **87**, 133603 (2001).
- [15] J. Kim, O. Benson, H. Kan, and Y. Yamamoto, *A single-photon turnstile device*, *Nature* **397**, 500 (1999).
- [16] P. Michler, A. Kiraz, C. Becher, W. V. Schoenfeld, P. M. Petroff, L. Zhang, E. Hu, and A. Imamoglu, *A Quantum Dot Single-Photon Turnstile Device*, *Science* **290**, 2282 (2000).
- [17] N. Akopian, N. H. Lindner, E. Poem, Y. Berlatzky, J. Avron, D. Gershoni, B. D. Gerardot, and P. M. Petroff, *Entangled Photon Pairs from Semiconductor Quantum Dots*, *Phys. Rev. Lett.* **96**, 130501 (2006).
- [18] R. M. Stevenson, R. J. Young, P. Atkinson, K. Cooper, D. A. Ritchie, and A. J. Shields, *A semiconductor source of triggered entangled photon pairs*, *Nature* **439**, 179 (2006).
- [19] J. Fischer, *Spin Decoherence of Electrons and Holes in Semiconductor Quantum Dots*, PhD Thesis, D. Loss (2010).

-
- [20] R. Raussendorf and H. J. Briegel, *A One-Way Quantum Computer*, Phys. Rev. Lett. **86**, 22, 5188 (2001).
- [21] R. Raussendorf, D. E. Browne, and H. J. Briegel, *Measurement-based quantum computation on cluster states*, Phys. Rev. A **68**, 2, 022312 (2003).
- [22] S. D. Barrett and P. Kok, *Efficient high-fidelity quantum computation using matter qubits and linear optics*, Phys. Rev. A **71**, 6, 060310 (2005).
- [23] Y. L. Lim, S. D. Barrett, A. Beige, P. Kok, and L. C. Kwek, *Repeat-until-success quantum computing using stationary and flying qubits*, Phys. Rev. A **73**, 1, 012304 (2006).
- [24] N. G. Stoltz, M. Rakher, S. Strauf, A. Badolato, D. D. Lofgreen, P. M. Petroff, L. A. Coldren, and D. Bouwmeester, *High-quality factor optical microcavities using oxide apertured micropillars*, Appl. Phys. Lett. **87**, 3, 031105 (2005).
- [25] O. Gywat, H.-A. Engel, D. Loss, R. J. Epstein, F. M. Mendoza, and D. D. Awschalom, *Optical detection of single-electron spin decoherence in a quantum dot*, Phys. Rev. B **69**, 20, 205303 (2004).
- [26] C. Bonato, F. Haupt, S. S. R. Oemrawsingh, J. Gudat, D. Ding, M. P. van Exter, and D. Bouwmeester, *CNOT and Bell-state analysis in the weak-coupling cavity QED regime*, Phys. Rev. Lett. **104**, 16, 160503 (2010).
- [27] T. Fujisawa, D. G. Austing, Y. Tokura, Y. Hirayama, and S. Tarucha, *Allowed and forbidden transitions in artificial hydrogen and helium atoms*, Nature **419**, 278 (2002).
- [28] J. M. Elzerman, R. Hanson, L. H. Willems van Beveren, B. Witkamp, L. M. K. Vandersypen, and L. P. Kouwenhoven, *Single-shot read-out of an individual electron spin in a quantum dot*, Nature **430**, 431 (2004).
- [29] A. S. Bracker, E. A. Stinaff, D. Gammon, M. E. Ware, J. G. Tischler, A. Shabaev, A. L. Efros, D. Park, D. Gershoni, V. L. Korenev, and I. A. Merkulov, *Optical Pumping of the Electronic and Nuclear Spin of Single Charge-Tunable Quantum Dots*, Phys. Rev. Lett. **94**, 4, 047402 (2005).
- [30] F. H. L. Koppens, J. A. Folk, J. M. Elzerman, R. Hanson, L. H. W. van Beveren, I. T. Vink, H. P. Tranitz, W. Wegscheider, L. P. Kouwenhoven, and L. M. K. Vandersypen, *Control and Detection of Singlet-Triplet Mixing in a Random Nuclear Field*, Science **309**, 5739, 1346 (2005).

- [31] A. C. Johnson, J. R. Petta, J. M. Taylor, A. Yacoby, M. D. Lukin, C. M. Marcus, M. P. Hanson, and A. C. Gossard, *Triplet-singlet spin relaxation via nuclei in a double quantum dot*, Nature **435**, 925 (2005).
- [32] D. J. Reilly, J. M. Taylor, J. R. Petta, C. M. Marcus, M. P. Hanson, and A. C. Gossard, *Suppressing Spin Qubit Dephasing by Nuclear State Preparation*, Science **321**, 5890, 817 (2008).
- [33] W. Yao, R.-B. Liu, and L. J. Sham, *Theory of electron spin decoherence by interacting nuclear spins in a quantum dot*, Phys. Rev. B **74**, 19, 195301 (2006).
- [34] J. A. Gupta and D. D. Awschalom, *Spin precession and the optical Stark effect in a semiconductor-doped glass*, Phys. Rev. B **63**, 8, 085303 (2001).
- [35] J. A. Gupta, R. Knobel, N. Samarth, and D. D. Awschalom, *Ultra-fast Manipulation of Electron Spin Coherence*, Science **292**, 5526, 2458 (2001).
- [36] O. Gywat, H. J. Krenner, and J. Berezovsky, *Spins in Optically Active Quantum Dots Concepts and Methods*, Wiley-VCH (2009).
- [37] M. Bayer, P. Hawrylak, K. Hinzer, S. Fafard, M. Korkusinski, Z. R. Wasilewski, O. Stern, and A. Forchel, *Coupling and Entangling of Quantum States in Quantum Dot Molecules*, Science **291**, 5503, 451 (2001).
- [38] K. J. Vahala, *Optical microcavities*, Nature **424**, 6950, 839 (2003).
- [39] H. Lee, J. Johnson, M. He, J. Speck, and P. Petroff, *Strain engineered self-assembled semiconductor quantum dot lattices*, Appl. Phys. Lett. **78**, 105 (2001).
- [40] T. D. Happ, I. I. Tartakovskii, V. D. Kulakovskii, J.-P. Reithmaier, M. Kamp, and A. Forchel, *Enhanced light emission of $In_xGa_{1-x}As$ quantum dots in a two-dimensional photonic-crystal defect microcavity*, Phys. Rev. B **66**, 4, 041303 (2002).
- [41] A. Badolato, K. Hennessy, M. Atatüre, J. Dreiser, E. Hu, P. M. Petroff, and A. Imamoglu, *Deterministic Coupling of Single Quantum Dots to Single Nanocavity Modes*, Science **308**, 5725, 1158 (2005).
- [42] S. Reitzenstein, C. Hofmann, A. Gorbunov, M. Strauß, A. L. S. H. M. K. S. H. Kwon, C. Schneider, and A. Forchel, *AlAs/GaAs micropillar cavities with quality factors exceeding 150.000*, Appl. Phys. Lett. **90**, 251109 (2007).

- [43] C. Zinoni, B. Alloing, C. Paranthoën, and A. Fiore, *Three-dimensional wavelength-scale confinement in quantum dot microcavity light-emitting diodes*, Appl. Phys. Lett. **85**, 12 (2004).
- [44] D. J. P. Ellis, A. J. Bennett, S. J. Dewhurst, P. Atkinson, C. A. Nicoll, D. A. Ritchie, and A. J. Shields, *Oxide-apertured microcavity single-photon-emitting diodes – simultaneous confinement of current and light*, Journal of Physics: Condensed Matter **20**, 45 (2008).
- [45] P. Michler, *Single Quantum Dots - Fundamentals, Applications and New Concepts*, Springer, "third" edition (2003).
- [46] C. Gerry and P. Knight, *Introductory Quantum Optics*, Cambridge University Press, "first" edition (2004).
- [47] H. Römer, *Theoretical Optics - An Introduction*, WILEY-VCH Verlag, "first" edition (2005).
- [48] H. J. Kimble, *Strong Interactions of Single Atoms and Photons in Cavity QED*, Physica Scripta **T76**, 127 (1998).
- [49] G. Khitrova, H. M. Gibbs, M. Kira, S. W. Koch, and A. Scherer, *Vacuum Rabi splitting in semiconductors*, Nature Physics **2**, 2, 81 (2006).
- [50] M. Fox, *Quantum Optics - An Introduction*, Oxford Master Series in Physics, 1st edition (2006).
- [51] E. Jaynes and F. Cummings, *Comparison of quantum and semiclassical radiation theories with application to the beam maser*, Proceedings of the IEEE **51**, 1, 89 (1963).
- [52] K. Vahala, *Optical Microcavities Ch. 4*, World Scientific Publishing Co. Pte. Ltd.,Singapore (2005).
- [53] E. Purcell, H. Torrey, and R. Pound, *Resonance Absorption by Nuclear Magnetic Moments in a Solid*, Physical Review **69**, 37 (1946).
- [54] A. Auffèves-Garnier, C. Simon, J.-M. Gérard, and J.-P. Poizat, *Giant optical nonlinearity induced by a single two-level system interacting with a cavity in the Purcell regime*, Phys. Rev. A **75**, 5, 053823 (2007).
- [55] M. T. Rakher, N. G. Stoltz, L. A. Coldren, P. M. Petroff, and D. Bouwmeester, *Externally Mode-Matched Cavity Quantum Electrodynamics with Charge-Tunable Quantum Dots*, Phys. Rev. Lett. **102**, 9, 097403 (2009).

- [56] S. Strauf, N. G. Stoltz, M. T. Rakher, L. A. Coldren, P. M. Petroff, and D. Bouwmeester, *High-frequency single-photon source with polarization control*, Nature Photonics **1**, 704 (2007).
- [57] A. Kiraz, P. Michler, C. Becher, B. Gayral, A. Imamoglu, L. Zhang, E. Hu, W. V. Schoenfeld, and P. M. Petroff, *Cavity-quantum electrodynamics using a single InAs quantum dot in a microdisk structure*, Appl. Phys. Lett. **78**, 25, 3932 (2001).
- [58] D. L. Huffaker, D. G. Deppe, and T. J. Rogers, *Transverse mode behavior in native-oxide-defined low threshold vertical-cavity lasers*, Appl. Phys. Lett. **65**, 13, 1611 (1994).
- [59] H. Li, L. L. Timothy, M. J. G., and R. A. Morgan, *Transverse modes and patterns of electrically pumped vertical-cavity surface-emitting semiconductor lasers*, Chaos, Solitons and Fractals **4**, 8-9, 1619 (1994), <ce:title>Special Issue: Nonlinear Optical Structures, Patterns, Chaos</ce:title>.
- [60] J. E. Epler, S. Gehrsitz, K. H. Gulden, M. Moser, H. Sigg, and H. W. Lehmann, *Mode behavior and high resolution spectra of circularly-symmetric GaAs-AlGaAs air-post vertical cavity surface emitting lasers*, Appl. Phys. Lett. **69**, 6 (1996).
- [61] C. Degen, W. Elsaber, and I. Fischer, *Transverse modes in oxide confined VCSELs: Influence of pump profile, spatial hole burning, and thermal effects*, Optics Express **5**, 3, 38 (1999).
- [62] M. Torre, A. Valle, and L. Pesquera, *Polarization and Transverse Mode Behaviour of VCSELs under Optical Injection*, Optical and Quantum Electronics **38**, 4-6, 445 (2006).
- [63] J. Gérard, D. Barrier, J. Marzin, R. Kuszelewicz, L. Manin, E. Costard, V. Thierry-Mieg, and T. Rivera, *Quantum boxes as active probes for photonic microstructures: The pillar microcavity case*, Appl. Phys. Lett. **69**, 4, 449 (1996).
- [64] E. R. Hegblom, D. I. Babic, B. J. Thibeault, and L. A. Coldren, *Estimation of scattering losses in dielectrically apertured vertical cavity lasers*, Appl. Phys. Lett. **68**, 13, 1757 (1996).
- [65] R. Naone, E. Hegblom, B. Thibeault, and L. Coldren, *Oxidation of Al-GaAs layers for tapered apertures in vertical-cavity lasers*, Electronic Letters **33**, 4, 300 (1997).

- [66] A. Yariv, *Quantum Electronics*, John Willey & Sons, "third" edition (1998).
- [67] D. Englund, D. Fattal, E. Waks, G. Solomon, B. Zhang, T. Nakaoka, Y. Arakawa, Y. Yamamoto, and J. Vučković, *Controlling the Spontaneous Emission Rate of Single Quantum Dots in a Two-Dimensional Photonic Crystal*, Phys. Rev. Lett. **95**, 1, 013904 (2005).
- [68] S. J. van Enk, J. I. Cirac, and P. Zoller, *Ideal Quantum Communication over Noisy Channels: A Quantum Optical Implementation*, Phys. Rev. Lett. **78**, 22, 4293 (1997).
- [69] T. Puppe, P. Maunz, T. Fischer, P. W. H. Pinkse, and G. Rempe, *Single-Atom Trajectories in Higher-Order Transverse Modes of a High-Finesse Optical Cavity* **T112** (2004).
- [70] P. Maunz, T. Puppe, T. Fischer, P. W. H. Pinkse, and G. Rempe, *Emission pattern of an atomic dipole in a high-finesse optical cavity*, Optics Letters **28**, 46 (2003).
- [71] C. Bonato, D. Ding, J. Gudat, S. Thon, H. Kim, P. Petroff, M. van Exter, and D. Bouwmeester, *Tuning micropillar cavity birefringence by laser induced surface defects*, Appl. Phys. Lett. **95**, 251104 (2009).
- [72] J. Gudat, C. Bonato, E. van Nieuwenburg, S. Thon, H. Kim, P. Petroff, M. P. van Exter, and D. Bouwmeester, *Permanent tuning of quantum dot transitions to degenerate microcavity resonances*, Appl. Phys. Lett. **98**, 121111 (2011).
- [73] C. Bonato, E. van Nieuwenburg, J. Gudat, S. Thon, H. Kim, M. P. van Exter, and D. Bouwmeester, *Strain tuning of quantum dot optical transitions via laser-induced surface defects*, Phys. Rev. B **84**, 075306 (2011).
- [74] K. Hennessy, A. Badolato, A. Tamboli, P. M. Petroff, E. Hu1, M. Atatüre, J. Dreiser, and A. Imamoglu, *Tuning photonic crystal nanocavity modes by wet chemical digital etching*, Appl. Phys. Lett. **87**, 021108 (2005).
- [75] A. Faraon, D. Englund, D. Bulla, B. Luther-Davies, B. J. Eggleton, N. Stoltz, P. Petroff, and J. Vučković, *Local tuning of photonic crystal cavities using chalcogenide glasses*, Appl. Phys. Lett. **92**, 043123 (2008).

- [76] D. Sridharan, E. Waks, G. Solomon, and J. Fourkas, *Reversible tuning of photonic crystal cavities using photochromic thin films*, Appl. Phys. Lett. **96**, 153303 (2010).
- [77] K. Hennessy, C. Högerle, E. Hu, A. Badolato, and A. Imamoğlu, *Tuning photonic nanocavities by atomic force microscope nano-oxidation*, Appl. Phys. Lett. **89**, 041118 (2006).
- [78] D. Erickson, T. Rockwood, T. Emery, A. Scherer, and D. Psaltis, *Nanofluidic tuning of photonic crystal circuits*, Opt. Lett. **31**, 59 (2006).
- [79] F. Intontil, S. Vignolini, V. TÅ¼rck, M. Colocci, P. Bettotti, L. Pavesi, S. L. Schweizer, R. Wehrspohn, and D. Wiersma, *Rewritable photonic circuits*, Appl. Phys. Lett. **89**, 211117 (2006).
- [80] S. Mosor, J. Hendrickson, B. C. Richards, J. Sweet, G. Khitrova, H. M. Gibbs, T. Yoshie, A. Scherer, O. B. Shchekin, and D. G. Deppe, *Scanning a photonic crystal slab nanocavity by condensation of xenon*, Appl. Phys. Lett. **87**, 141105 (2005).
- [81] P. W. Fry, I. E. Itskevich, D. J. Mowbray, M. S. Skolnick, J. J. Finley, J. A. Barker, E. P. O'Reilly, L. R. Wilson, I. A. Larkin, P. A. Maksym, M. Hopkinson, M. Al-Khafaji, J. P. R. David, A. G. Cullis, G. Hill, and J. C. Clark, *Inverted Electron-Hole Alignment in InAs-GaAs Self-Assembled Quantum Dots*, Phys. Rev. Lett. **84**, 4, 733 (2000).
- [82] C. Kistner, T. Heindel, C. Schneider, A. Rahimi-Iman, S. Reitzenstein, S. HÅ¶ffling, and A. Forchel, *Demonstration of strong coupling via electro-optical tuning in high-quality QD-micropillar systems*, Optics Express **16**, 15006 (2008).
- [83] A. Faraon, D. Englund, I. Fushman, J. Vučković, N. Stoltz, and P. M. Petroff, *Local quantum dot tuning on photonic crystal chips*, Appl. Phys. Lett. **90**, 213110 (2007).
- [84] A. Rastelli, A. Ulhaq, L. Kiravittaya, S. abd Wang, A. Zrenner, and O. G. Schmidt, *In situ laser microprocessing of single self-assembled quantum dots and optical microcavities*, Appl. Phys. Lett. **90**, 073120 (2007).
- [85] C. Obermüller, A. Deisenrieder, G. Abstreiter, K. Karrai, S. Grosse, S. Manus, J. Feldmann, H. Lipsanen, M. Söpanen, and J. Ahopelto, *Mechanical nanomanipulation of single strain-induced semiconductor quantum dots*, Appl. Phys. Lett. **75**, 358 (1999).

- [86] T. Zander, A. Herklotz, S. Kiravittaya, M. Benyoucef, F. Ding, P. Atkinson, S. Kumar, J. D. Plumhof, K. Dörr, A. Rastelli, and O. G. Schmidt, *Epitaxial quantum dots in stretchable optical microcavities*, Optics Express **17**, 22452 (2009).
- [87] G. W. Bryant, M. Zieliński, N. Malkova, J. Sims, W. Jaskólski, and J. Aizpurua, *Effect of Mechanical Strain on the Optical Properties of Quantum Dots: Controlling Exciton Shape, Orientation, and Phase with a Mechanical Strain*, Phys. Rev. Lett. **105**, 6, 067404 (2010).
- [88] S. Seidl, M. Kroner, A. Högele, K. Karrai, R. J. Warburton, A. Badolato, and P. M. Petroff, *Effect of uniaxial stress on excitons in a self-assembled quantum dot*, Appl. Phys. Lett. **88**, 203113 (2006).
- [89] P. Petroff, A. Lorke, and A. Imamoğlu, *Epitaxial Self-assembled Quantum Dots*, Physics Today **54**, 050000, 46 (2001).
- [90] A. K. J. van Doorn, M. P. van Exter, and J. P. Woerdman, *Elasto-optic anisotropy and polarization orientation of vertical-cavity surface-emitting semiconductor lasers*, Appl. Phys. Lett. **69**, 1041 (1996).
- [91] A. K. J. van Doorn, M. P. van Exter, and J. P. Woerdman, *Tailoring the birefringence in a vertical-cavity semiconductor laser*, Appl. Phys. Lett. **69**, 3635 (1996).
- [92] A. Högele, S. Seidl, M. Kroner, K. Karrai, R. J. Warburton, B. D. Gerardot, and P. M. Petroff, *Voltage-Controlled Optics of a Quantum Dot*, Phys. Rev. Lett. **93**, 21, 217401 (2004).
- [93] C. D. Watson, M. Poirier, J. M. Heaton, M. Lewis, and M. Boudreau, *Acoustooptic Resonance in Deep-Etched GaAs-AlGaAs Electrooptic Modulators*, J. of Lightwave Technology **22**, 1598 (2004).
- [94] R. J. Warburton, C. Schaflein, D. Haft, F. Bickel, A. Lorke, K. Karrai, J. M. Garcia, W. Schoenfeld, and P. M. Petroff, *Optical emission from a charge-tunable quantum ring*, Nature **405** (2000).
- [95] M. A. Cusack, P. R. Briddon, and M. Jaros, *Electronic structure of InAs/GaAs self-assembled quantum dots*, Phys. Rev. B **54**, 4, R2300 (1996).
- [96] L. Seravalli, M. Minelli, P. Frigeri, P. Allegri, V. Avanzini, and S. Franchi, *The effect of strain on tuning of light emission of energy of InAs/InGaAs quantum-dot nanostructures*, Appl. Phys. Lett. **82**, 2341 (2003).

- [97] P. Kent, G. L. W. Hart, and A. Zunger, *Biaxial strain-modified valence and conduction band offsets of zinc-blende GaN, GaP, GaAs, InN, InP, and InAs, and optical bowing of strained epitaxial InGaN alloys*, Appl. Phys. Lett. **81**, 4377 (2002).
- [98] A. K. J. van Doorn, M. P. van Exter, and J. P. Woerdman, *Strain-induced birefringence in vertical-cavity semiconductor lasers*, IEEE J. Quantum Electron. **34**, 700 (1998).
- [99] S. L. Chuang, *Physics of Optoelectronic Devices*, Wiley, "first" edition (1995).
- [100] L. C. Andreani, A. Pasquarello, and F. Bassani, *Hole subbands in strained GaAs-Ga_{1-x}Al_xAs quantum wells: Exact solution of the effective-mass equation*, Phys. Rev. B **36**, 5887 (1987).
- [101] M. Grundmann, O. Stier, and D. Bimberg, *InAs/GaAs pyramidal quantum dots: Strain distribution, optical phonons, and electronic structure*, Phys. Rev. B **52**, 11969 (1995).
- [102] S.-S. Li, J.-B. Xia, Z. L. Yuan, Z. Y. Xu, W. Ge, X. R. Wang, Y. Wang, J. Wang, and L. L. Chang, *Effective-mass theory for InAs/GaAs strained coupled quantum dots*, Phys. Rev. B **54**, 11575 (1996).
- [103] M. Tadić, F. M. Peeters, and K. L. Janssens, *Effect of isotropic versus anisotropic elasticity on the electronic structure of cylindrical InP/In_{0.49}Ga_{0.51}P self-assembled quantum dots*, Phys. Rev. B **65**, 165333 (2002).
- [104] G. W. Bryant, *Excitons in quantum boxes: Correlation effects and quantum confinement*, Phys. Rev. B **37**, 8763 (1988).
- [105] A. Franceschetti and A. Zunger, *Direct Pseudopotential Calculation of Exciton Coulomb and Exchange Energies in Semiconductor Quantum Dots*, Phys. Rev. Lett. **78**, 915 (1997).
- [106] A. Nazir, B. W. Lovett, S. Barrett, J. Reina, and G. A. D. Briggs, *Anticrossings in Förster coupled quantum dots*, Phys. Rev. B **71**, 045334 (2005).
- [107] E. Biolatti, I. D'Amico, P. Zanardi, and F. Rossi, *Electro-optical properties of semiconductor quantum dots: Application to quantum information processing*, Phys. Rev. B **65**, 075306 (2002).

- [108] B. J. Riel, *An introduction to self-assembled quantum dots*, American Journal of Physics **76**, 750 (2008).
- [109] S. Thon, M. Rakher, H. Kim, J. Gudat, W. Irvine, P. Petroff, and D. Bouwmeester, *Strong coupling through optical positioning of a quantum dot in a photonic crystal cavity*, Appl. Phys. Lett. **94**, 111115 (2009).
- [110] S. Thon, H. Kim, C. Bonato, J. Gudat, J. Hagemeyer, P. M. Petroff, and D. Bouwmeester, *Independent electrical tuning of separated quantum dots in coupled photonic crystal cavities*, Appl. Phys. Lett. **99**, 161102 (2011).
- [111] L. Childress, J. M. Taylor, A. S. Sørensen, and M. D. Lukin, *Fault-Tolerant Quantum Communication Based on Solid-State Photon Emitters*, Phys. Rev. Lett. **96**, 070504 (2006).
- [112] C. Simon and J.-P. Poizat, *Creating Single Time-Bin-Entangled Photon Pairs*, Phys. Rev. Lett. **94**, 030502 (2005).
- [113] E. Knill, R. Laflamme, and G. J. Milburn, *A scheme for efficient quantum computation with linear optics*, Nature **409**, 46 (2001).
- [114] D. Englund, A. Faraon, I. Fushman, N. Stoltz, P. Petroff, and J. Vučković, *Controlling cavity reflectivity with a single quantum dot*, Nature **450**, 857 (2007).
- [115] K. Hennessy, A. Badolato, M. Winger, D. Gerace, M. Atatüre, S. Gulde, S. Falt, E. L. Hu, and A. Imamoglu, *Quantum nature of a strongly coupled single quantum dot-cavity system*, Nature **445**, 896 (2007).
- [116] M. Winger, A. Badolato, K. J. Hennessy, E. L. Hu, and A. Imamoglu, *Quantum Dot Spectroscopy Using Cavity Quantum Electrodynamics*, Phys. Rev. Lett. **101**, 226808 (2008).
- [117] A. Yildiz, J. N. Forkey, S. A. McKinney, T. Ha, Y. E. Goldman, and P. R. Selvin, *Myosin V Walks Hand-Over-Hand: Single Fluorophore Imaging with 1.5-nm Localization*, Science **300**, 5628, 2061 (2003).
- [118] A. Yildiz, M. Tomishige, R. D. Vale, and P. R. Selvin, *Kinesin Walks Hand-Over-Hand*, Science **303**, 5658, 676 (2004).
- [119] F. De Martini, M. Marrocco, and D. Murra, *Transverse quantum correlations in the active microscopic cavity*, Phys. Rev. Lett. **65**, 15, 1853 (1990).

- [120] H. Deng, D. G. Deppe, and J. Shin, *Dependence of mode size and temporal response on the mirror contrast ratio in microcavity lasers*, Appl. Phys. Lett. **67**, 3526 (1995).
- [121] Y. Akahane, T. Asano, B.-S. Song, and S. Noda, *High-Q photonic nanocavity in a twodimensional photonic crystal*, Nature **425**, 944 (2003).
- [122] Y. Akahane, T. Asano, B.-S. Song, and S. Noda, *Fine-tuned high-Q photonic-crystal nanocavity*, Optics Express **13**, 1202 (2005).
- [123] S. Strauf, M. Rakher, I. Carmeli, K. Hennessy, C. Meier, A. Badolato, M. J. A. DeDood, P. Petroff, E. L. Hu, E. Gwinn, and D. Bouwmeester, *Frequency control of photonic crystal membrane resonators by monolayer deposition*, Appl. Phys. Lett. **88**, 043116 (2006).
- [124] L. C. Andreani, G. Panzarini, and J.-M. Gérard, *Strong-coupling regime for quantum boxes in pillar microcavities: Theory*, Phys. Rev. B **60**, 13276 (1999).
- [125] A. Faraon, I. Fushman, D. Englund, N. Stoltz, P. Petroff, and J. Vučković, *Dipole induced transparency in waveguide coupled photonic crystal cavities*, Opt. Express **16**, 12154 (2008).
- [126] A. Faraon, E. Waks, D. Englund, A. Fushman, and J. Vučković, *Efficient Photonic Crystal Cavity-Waveguide Couplers*, Appl. Phys. Lett. **90**, 073102 (2007).
- [127] J. F. Ziegler, J. P. Biersack, and U. Littmark, *The Stopping and Range of Ions in Solids*, Pergamon Press (1985).
- [128] J. Metz, M. Trupke, and A. Beige, *Robust Entanglement through Macroscopic Quantum Jumps*, Phys. Rev. Lett. **97**, 040503 (2006).
- [129] M. P. van Exter, J. Gudat, G. Nienhuis, and D. Bouwmeester, *Spin quantum jumps in a singly charged quantum dot*, Phys. Rev. A **80**, 2, 023812 (2009).
- [130] N. Bohr, *On the Constitution of Atoms and Molecules*, Philosophical Magazine **26**, 1 (1913).
- [131] E. Schrödinger, *An Undulatory Theory of the Mechanics of Atoms and Molecules*, Phys. Rev. **28**, 6, 1049 (1926).
- [132] H. G. Dehmelt, *Proposed $10^{14}\Delta\nu < \nu$ Laser Fluorescence Spectroscopy on Tl^+ Mono-Ion Oscillator II (spontaneous quantum jumps)*, Bull. Am. Phys. Soc. **20**, 60 (1975).

- [133] G. Nienhuis, *Impressed by light: Mechanical action of radiation on atomic motion*, Physics Reports **138**, 3, 151 (1986).
- [134] J. Dalibard, Y. Castin, and K. Mølmer, *Wave-function approach to dissipative processes in quantum optics*, Phys. Rev. Lett. **68**, 5, 580 (1992).
- [135] D. Bouwmeester, R. J. C. Spreeuw, G. Nienhuis, and J. P. Woerdman, *Neoclassical radiation theory as an integral part of the Monte Carlo wave-function method*, Phys. Rev. A **49**, 5, 4170 (1994).
- [136] A. Imamoglu, D. D. Awschalom, G. Burkard, D. P. DiVincenzo, D. Loss, M. Sherwin, and A. Small, *Quantum Information Processing Using Quantum Dot Spins and Cavity QED*, Phys. Rev. Lett. **83**, 20, 4204 (1999).
- [137] A. J. Ramsay, S. J. Boyle, R. S. Kolodka, J. B. B. Oliveira, J. Skiba-Szymanska, H. Y. Liu, M. Hopkinson, A. M. Fox, and M. S. Skolnick, *Fast Optical Preparation, Control, and Readout of a Single Quantum Dot Spin*, Phys. Rev. Lett. **100**, 19, 197401 (2008).
- [138] X. Xu, B. Sun, P. R. Berman, D. G. Steel, A. S. Bracker, D. Gammon, and L. J. Sham, *Coherent population trapping of an electron spin in a single negatively charged quantum dot*, Nat. Phys. **4**, 9, 692 (2008).
- [139] M. Paillard, X. Marie, P. Renucci, T. Amand, A. Jbeli, and J. M. Gérard, *Spin Relaxation Quenching in Semiconductor Quantum Dots*, Phys. Rev. Lett. **86**, 8, 1634 (2001).
- [140] J. M. Taylor, J. R. Petta, A. C. Johnson, A. Yacoby, C. M. Marcus, and M. D. Lukin, *Relaxation, dephasing, and quantum control of electron spins in double quantum dots*, Phys. Rev. B **76**, 3, 035315 (2007).
- [141] J. M. Gérard, B. Sermage, B. Gayral, B. Legrand, E. Costard, and V. Thierry-Mieg, *Enhanced Spontaneous Emission by Quantum Boxes in a Monolithic Optical Microcavity*, Phys. Rev. Lett. **81**, 5, 1110 (1998).
- [142] M. Bayer, T. L. Reinecke, F. Weidner, A. Larionov, A. McDonald, and A. Forchel, *Inhibition and Enhancement of the Spontaneous Emission of Quantum Dots in Structured Microresonators*, Phys. Rev. Lett. **86**, 14, 3168 (2001).
- [143] M. Atatüre, J. Dreiser, A. Badolato, and A. Imamoglu, *Observation of Faraday rotation from a single confined spin*, Nature **3**, 101 (2007).

- [144] J. Berezovsky, M. H. Mikkelsen, N. G. Stoltz, L. A. Coldren, and D. D. Awschalom, *Picosecond Coherent Optical Manipulation of a Single Electron Spin in a Quantum Dot*, *Science* **320**, 5874, 349 (2008).
- [145] H. G. Dehmelt, *Proposed $10^{14}\Delta\nu < \nu$ Laser Fluorescence Spectroscopy on Tl^+ Mono-Ion Oscillator*, *Bull. Am. Phys. Soc.* **18**, 1521 (1973).
- [146] R. J. Cook and H. J. Kimble, *Possibility of Direct Observation of Quantum Jumps*, *Phys. Rev. Lett.* **54**, 10, 1023 (1985).
- [147] D. J. Wineland and W. M. Itano, *Spectroscopy of a single Mg^+ ion*, *Physics Letters A* **82**, 2, 75 (1981).
- [148] J. C. Bergquist, R. G. Hulet, W. M. Itano, and D. J. Wineland, *Observation of Quantum Jumps in a Single Atom*, *Phys. Rev. Lett.* **57**, 14, 1699 (1986).
- [149] H. J. Kimble, R. J. Cook, and A. L. Wells, *Intermittent atomic fluorescence*, *Phys. Rev. A* **34**, 4, 3190 (1986).
- [150] K. T. Shimizu, R. G. Neuhauser, C. A. Leatherdale, S. A. Empedocles, W. K. Woo, and M. G. Bawendi, *Blinking statistics in single semiconductor nanocrystal quantum dots*, *Phys. Rev. B* **63**, 20, 205316 (2001).
- [151] M. B. Plenio and P. L. Knight, *The quantum-jump approach to dissipative dynamics in quantum optics*, *Rev. Mod. Phys.* **70**, 1, 101 (1998).
- [152] V. Delgado and J. M. Gomez Llorente, *Weak-coupling-like time evolution of driven four-level systems in the strong-coupling regime*, *Phys. Rev. A* **68**, 022503 (2003).
- [153] J. Fischer, T. Trif, W. Coish, and D. Loss, *Spin interactions, relaxation and decoherence in quantum dots*, *Solid State Communications* **149**, 35-36, 1443 (2009), *fundamental Phenomena and Applications of Quantum Dots*.
- [154] R. Hanson, L. P. Kouwenhoven, J. R. Petta, S. Tarucha, and L. M. K. Vandersypen, *Spins in few-electron quantum dots*, *Rev. Mod. Phys.* **79**, 4, 1217 (2007).
- [155] B. Eble, C. Testelin, P. Desfonds, F. Bernardot, A. Balocchi, T. Amand, A. Miard, A. Lemaître, X. Marie, and M. Chamarro, *Hole-Nuclear Spin Interaction in Quantum Dots*, *Phys. Rev. Lett.* **102**, 14, 146601 (2009).

-
- [156] A. Högele, B. Alèn, F. Bickel, R. J. Warburton, P. M. Petroff, and K. Karrai, *Exciton fine structure splitting of single InGaAs self-assembled quantum dots*, Physica E: Low-dimensional Systems and Nanostructures **21**, 2-4, 175 (2004), proceedings of the Eleventh International Conference on Modulated Semiconductor Structures.
- [157] M. Bayer, G. Ortner, O. Stern, A. Kuther, A. A. Gorbunov, A. Forchel, P. Hawrylak, S. Fafard, K. Hinzer, T. L. Reinecke, S. N. Walck, J. P. Reithmaier, F. Klopff, and F. Schäfer, *Fine structure of neutral and charged excitons in self-assembled In(Ga)As/(Al)GaAs quantum dots*, Phys. Rev. B **65**, 19, 195315 (2002).
- [158] B. Gerardot, D. Brunner, P. A. Dalgarno, P. Ohberg, S. Seidl, M. Kroner, K. Karrai, N. G. Stoltz, P. M. Petroff, and R. J. Warburton, *Optical pumping of a single hole spin in a quantum dot*, Nature **451**, 441 (2008).
- [159] G. J. Milburn, *Quantum Zeno effect and motional narrowing in a two-level system*, J. Opt. Soc. Am. B **5**, 6, 1317 (1988).
- [160] G. Nienhuis, *Theory of quantum jumps in three-state atoms*, Phys. Rev. A **35**, 11, 4639 (1987).
- [161] T. Basché, W. E. Moerner, M. Orrit, and H. Talon, *Photon antibunching in the fluorescence of a single dye molecule trapped in a solid*, Phys. Rev. Lett. **69**, 10, 1516 (1992).
- [162] C. W. Gardiner and M. J. Collett, *Input and output in damped quantum systems: Quantum stochastic differential equations and the master equation*, Phys. Rev. A **31**, 6, 3761 (1985).
- [163] O. Benson and Y. Yamamoto, *Master-equation model of a single-quantum-dot microsphere laser*, Phys. Rev. A **59**, 6, 4756 (1999).
- [164] L.-M. Duan and H. J. Kimble, *Scalable Photonic Quantum Computation through Cavity-Assisted Interactions*, Phys. Rev. Lett. **92**, 12, 127902 (2004).
- [165] C. Schön, K. Hammerer, M. M. Wolf, J. I. Cirac, and E. Solano, *Sequential generation of matrix-product states in cavity QED*, Phys. Rev. A **75**, 3, 032311 (2007).
- [166] S. Devitt, A. D. Greentree, R. Ionicioiu, J. L. O'Brien, W. J. Munro, and L. C. L. Hollenberg, *Photonic module: An on-demand resource for photonic entanglement*, Phys. Rev. A **76**, 5, 052312 (2007).

- [167] B. B. Blinov, D. L. Moehring, L.-M. Duan, and C. Monroe, *Observation of entanglement between a single trapped atom and a single photon*, Nature **428**, 153 (2004).
- [168] B. Weber, H. P. Specht, T. Müller, J. Bochmann, M. Mücke, D. L. Moehring, and G. Rempe, *Photon-Photon Entanglement with a Single Trapped Atom*, Phys. Rev. Lett. **102**, 3, 030501 (2009).
- [169] R. Blatt and D. Wineland, *Entangled states of trapped atomic ions*, Nature **453**, 1008 (2008).
- [170] A. Wallraff, D. I. Schuster, A. Blais, L. Frunzio, R.-S. Huang, J. Majer, S. Kumar, S. M. Girvin, and R. J. Schoelkopf, *Strong coupling of a single photon to a superconducting qubit using circuit quantum electrodynamics*, Nature **431**, 162 (2004).
- [171] M. Ansmann, H. Wang, R. C. Bialczak, M. Hofheinz, E. Lucero, M. Neeley, A. D. O'Connell, D. Sank, M. Weides, J. Wenner, A. N. Cleland, and J. M. Martinis, *Violation of Bell's inequality in Josephson phase qubits*, Nature **461**, 504.
- [172] T. Calarco, A. Datta, P. Fedichev, E. Pazy, and P. Zoller, *Spin-based all-optical quantum computation with quantum dots: Understanding and suppressing decoherence*, Phys. Rev. A **68**, 1, 012310 (2003).
- [173] C. Monroe, *Quantum information processing with atoms and photons*, Nature **416**, 238 (2002).
- [174] C. Y. Hu, A. Young, J. L. O'Brien, W. J. Munro, and J. G. Rarity, *Giant optical Faraday rotation induced by a single-electron spin in a quantum dot: Applications to entangling remote spins via a single photon*, Phys. Rev. B **78**, 8, 085307 (2008).
- [175] C. Y. Hu, W. J. Munro, and J. G. Rarity, *Deterministic photon entangler using a charged quantum dot inside a microcavity*, Phys. Rev. B **78**, 12, 125318 (2008).
- [176] J. Shen and S. Fan, *Coherent photon transport from spontaneous emission in one-dimensional waveguides*, Opt. Lett. **30**, 15, 2001 (2005).
- [177] E. Waks and J. Vučković, *Dipole Induced Transparency in Drop-Filter Cavity-Waveguide Systems*, Phys. Rev. Lett. **96**, 15, 153601 (2006).
- [178] C. Y. Hu, W. J. Munro, J. L. O'Brien, and J. G. Rarity, *Proposed entanglement beam splitter using a quantum-dot spin in a double-sided optical microcavity*, Phys. Rev. B **80**, 20, 205326 (2009).

- [179] J. Calsamiglia and N. Luetkenhaus, *Maximum efficiency of a linear-optical Bell-state analyzer*, Appl. Phys. B **72**, 67 (2001).
- [180] Y.-H. Kim, S. P. Kulik, and Y. Shih, *Quantum Teleportation of a Polarization State with a Complete Bell State Measurement*, Phys. Rev. Lett. **86**, 7, 1370 (2001).
- [181] P. G. Kwiat and H. Weinfurter, *Embedded Bell-state analysis*, Phys. Rev. A **58**, 4, R2623 (1998).
- [182] S. P. Walborn, S. Pádua, and C. H. Monken, *Hyperentanglement-assisted Bell-state analysis*, Phys. Rev. A **68**, 4, 042313 (2003).
- [183] A. Barenco, D. Deutsch, A. Ekert, and R. Jozsa, *Conditional Quantum Dynamics and Logic Gates*, Phys. Rev. Lett. **74**, 20, 4083 (1995).
- [184] S. M. Clark, K.-M. C. Fu, Q. Zhang, T. D. Ladd, C. Stanley, and Y. Yamamoto, *Ultrafast Optical Spin Echo for Electron Spins in Semiconductors*, Phys. Rev. Lett. **102**, 24, 247601 (2009).
- [185] D. Press, T. Ladd, B. Zhang, and Y. Yamamoto, *Complete quantum control of a single quantum dot spin using ultrafast optical pulses*, Nature **456**, 218 (2008).
- [186] R. Oulton, A. Greilich, S. Y. Verbin, R. V. Cherbunin, T. Auer, D. R. Yakovlev, M. Bayer, I. A. Merkulov, V. Stavarache, D. Reuter, and A. D. Wieck, *Subsecond Spin Relaxation Times in Quantum Dots at Zero Applied Magnetic Field Due to a Strong Electron-Nuclear Interaction*, Phys. Rev. Lett. **98**, 10, 107401 (2007).
- [187] A. Greilich, A. Shabaev, D. R. Yakovlev, A. L. Efros, I. A. Yugova, D. Reuter, A. D. Wieck, and M. Bayer, *Nuclei-Induced Frequency Focusing of Electron Spin Coherence*, Science **317**, 5846, 1896 (2007).
- [188] I. T. Vink, K. C. Nowack, F. H. L. Koppens, J. Danon, Y. V. Nazarov, and L. M. K. Vandersypen, *Locking electron spins into magnetic resonance by electron-nuclear feedback*, Nat Phys pages 764–768 (2009).
- [189] C. Latta, A. Högele, Y. Zhao, A. N. Vamivakas, P. Maletinsky, M. Kroner, J. Dreiser, I. Carusotto, A. Badolato, D. Schuh, W. Wegscheider, M. Atatüre, and A. Imamoglu, *Confluence of resonant laser excitation and bidirectional quantum-dot nuclear-spin polarization*, Nat. Phys. **5**, 758–763 (2009).

- [190] F. Haupt, S. S. R. Oemrawsingh, S. Thon, H. Kim, D. Kleckner, D. Ding, D. J. Suntrup, P. M. Petroff, and D. Bouwmeester, *Fiber-connectorized micropillar cavities*, Appl. Phys. Lett. **97**, 131113 (2010).
- [191] F. Pobell, *Matter and Methods at Low Temperature*, Springer, 3rd edition (2007).