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*Citation for published version (APA):*

van Es, J. J. P. (2009). Bose-Einstein condensates in radio-frequency-dressed potentials on an atom chip  
Amsterdam

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# References

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- [1] The Royal Swedish Academy of Sciences. *Nobel Prize in Physics 1956: presentation speech by professor E.G. Rudberg*.  
[http://nobelprize.org/nobel\\_prizes/physics/laureates/1956/press.html](http://nobelprize.org/nobel_prizes/physics/laureates/1956/press.html)  
(1956). Retrieved 15 May 2008.
- [2] The Royal Swedish Academy of Sciences. *Nobel Prize in Physics 1964: presentation speech by professor B. Edlén*.  
[http://nobelprize.org/nobel\\_prizes/physics/laureates/1964/press.html](http://nobelprize.org/nobel_prizes/physics/laureates/1964/press.html)  
(1964). Retrieved 15 May 2008.
- [3] The Royal Swedish Academy of Sciences. *Nobel Prize in Physics 1981: Press release*.  
[http://nobelprize.org/nobel\\_prizes/physics/laureates/1981/press.html](http://nobelprize.org/nobel_prizes/physics/laureates/1981/press.html)  
(1981). Retrieved 15 May 2008.
- [4] The Royal Swedish Academy of Sciences. *Nobel Prize in Physics 1997: additional background information*.  
[http://nobelprize.org/nobel\\_prizes/physics/laureates/1997/back.html](http://nobelprize.org/nobel_prizes/physics/laureates/1997/back.html) (1997).  
Retrieved 15 May 2008.
- [5] The Royal Swedish Academy of Sciences. *Nobel Prize in Physics 2000: advanced information*.  
[http://nobelprize.org/nobel\\_prizes/physics/laureates/2000/adv.html](http://nobelprize.org/nobel_prizes/physics/laureates/2000/adv.html) (2000).  
Retrieved 8 May 2008.
- [6] The Royal Swedish Academy of Sciences. *Nobel Prize in Physics 2001: advanced information*.  
[http://nobelprize.org/nobel\\_prizes/physics/laureates/2001/adv.html](http://nobelprize.org/nobel_prizes/physics/laureates/2001/adv.html) (2001).  
Retrieved 8 May 2008.
- [7] W. Wien. *Ueber die Energievertheilung im Emissionsspectrum eines schwarzen Körpers*. *Annalen der Physik* **58**, 662–669 (1896).
- [8] H. Kragh. *Max Planck: The reluctant revolutionary*. *Physics World* **13**, 31–35 (2000).
- [9] A. Einstein. *Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt*. *Annalen der Physik* **17**, 132–148 (1905).
- [10] W. A. Blanpied. *Satyendranath Bose: Co-founder of quantum statistics*. *Am. J. Phys.* **40**, 1212–1220 (1972).

- [11] S. Bose. *Plancks Gesetz und Lichtquantenhypothese*. Z. Phys. **26**, 178 (1924).
- [12] A. Einstein. *Quantentheorie des einatomigen idealen Gases*. Sitzungsberichte der Preussischen Akademie der Wissenschaften zu Berlin 261–267 (1924).
- [13] A. Einstein. *Quantentheorie des einatomigen idealen Gases II*. Sitzungsberichte der Preussischen Akademie der Wissenschaften zu Berlin 3–14 (1925).
- [14] A. Einstein. *Zur Quantentheorie des idealen Gases*. Sitzungsberichte der Preussischen Akademie der Wissenschaften zu Berlin 18–25 (1925).
- [15] C. Kittel and H. Kroemer. *Thermal physics*. Freeman, New York (1980).
- [16] F. London. *On the Bose-Einstein condensation*. Phys. Rev. **54**(11), 947–954 (1938).
- [17] A. Pais. ‘*Subtle is the Lord...*’ *The Science and the Life of Albert Einstein*. Oxford University Press (1982).
- [18] H. J. Metcalf and P. van der Straten. *Laser Cooling and Trapping of Neutral Atoms*. Springer, New York (1999).
- [19] M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman, and E. A. Cornell. *Observation of Bose-Einstein condensation in a dilute atomic vapor*. Science **269**, 198–201 (1995).
- [20] K. B. Davis, M. O. Mewes, M. R. Andrews, N. J. van Druten, D. S. Durfee, D. M. Kurn, and W. Ketterle. *Bose-Einstein condensation in a gas of sodium atoms*. Phys. Rev. Lett. **75**(22), 3969–3973 (1995).
- [21] C. C. Bradley, C. A. Sackett, J. J. Tollett, and R. G. Hulet. *Evidence for Bose-Einstein condensation in an atomic gas with attractive interactions*. Phys. Rev. Lett. **75**(9), 1687–1690 (1995).
- [22] W. Ketterle. *Nobel lecture: When atoms behave as waves: Bose-Einstein condensation and the atom laser*. Rev. Mod. Phys. **74**, 1131 (2002).
- [23] E. A. Cornell and C. E. Wieman. *Nobel lecture: Bose-Einstein condensation in a dilute gas, the first 70 years and some recent experiments*. Rev. Mod. Phys. **74**, 875 (2002).
- [24] J. Bardeen and W. H. Brattain. *The transistor, a semi-conductor triode*. Phys. Rev. **74**, 230–231 (1948).
- [25] J. S. Kilby. *Miniaturized electronic circuits*. U. S. Patent 3138743 (Filed February 6, 1959. Issued June 23, 1964).
- [26] J. S. Kilby. *Invention of the integrated circuit*. IEEE Transactions in Electron Devices **ED-23**, 648–654 (1976).

- 
- [27] R. N. Noyce. *Semiconductor device-and-lead structure*. U. S. Patent 2981877 (Filed July 30, 1959. Issued April 25, 1961).
- [28] G.-T. Chiu and J. Shaw. *Optical lithography: Introduction*. IBM Journal of Research and Development **41**, 3–6 (1997).
- [29] K. Ronse. *Optical lithography — a historical perspective*. C. R. Physique **7**, 844–857 (2006).
- [30] A. Schawlow and C. Townes. *Infrared and optical masers*. Phys. Rev. **112**(6), 1940–1949 (1958).
- [31] J. L. Bromberg. *The birth of the laser*. Physics Today **41**(10), 26–33 (1988).
- [32] T. H. Maiman. *Stimulated optical radiation in ruby*. Nature **187**, 493–494 (1960).
- [33] T. H. Maiman. *Stimulated optical emission in fluorescent solids. I. Theoretical considerations*. Phys. Rev. **123**, 1145–1150 (1961).
- [34] H. Kroemer. *A proposed class of heterojunction injection lasers*. Proc. IEEE **51**, 1782 (1963).
- [35] S. Chu. *The manipulation of neutral particles*. Rev. Mod. Phys. **70**(3), 685–706 (1998).
- [36] C. N. Cohen-Tannoudji. *Manipulating atoms with photons*. Rev. Mod. Phys. **70**, 707–719 (1998).
- [37] W. D. Phillips. *Laser cooling and trapping of neutral atoms*. Rev. Mod. Phys. **70**(3), 721–741 (1998).
- [38] T. Hänsch and A. Schawlow. *Cooling of gases by laser radiation*. Opt. Commun. **13**, 68 (1975).
- [39] D. E. Pritchard. *Cooling neutral atoms in a magnetic trap for precision spectroscopy*. Phys. Rev. Lett. **51**(15), 1336–1339 (1983).
- [40] Y. V. Gott, M. S. Ioffe, and V. G. Tel’kovskii. *Some new results on confinement in magnetic traps*. Nucl. Fusion, Suppl. **Pt. 3**, 1045 and 1284 (1962).
- [41] E. L. Raab, M. Prentiss, A. Cable, S. Chu, and D. E. Pritchard. *Trapping of neutral sodium atoms with radiation pressure*. Phys. Rev. Lett. **59**, 2631–2634 (1987).
- [42] V. Bagnato, D. E. Pritchard, and D. Kleppner. *Bose-Einstein condensation in an external potential*. Phys. Rev. A **35**(10), 4354–4358 (1987).
- [43] W. Ketterle and N. J. van Druten. *Evaporative cooling of trapped atoms*. Advances in Atomic, Molecular and Optical Physics **37**, 181–236 (1996).

- [44] H. F. Hess. *Evaporative cooling of magnetically trapped and compressed spin-polarized hydrogen*. Phys. Rev. B **34**(5), 3476–3479 (1986).
- [45] K. Davis, M. Mewes, M. Joffe, M. Andrews, and W. Ketterle. *Evaporative cooling of sodium atoms*. Phys. Rev. Lett. **74**, 5202–5205 (1995).
- [46] J. D. Weinstein and K. G. Libbrecht. *Microscopic magnetic traps for neutral atoms*. Phys. Rev. A **52**(5), 4004–4009 (1995).
- [47] H. Ott, J. Fortágh, G. Schlotterbeck, A. Grossmann, and C. Zimmermann. *Bose-Einstein condensation in a surface microtrap*. Phys. Rev. Lett. **87**, 230401 (2001).
- [48] W. Hänsel, P. Hommelhoff, T. W. Hänsch, and J. Reichel. *Bose-Einstein condensation on a microelectronic chip*. Nature **413**, 498–501 (2001).
- [49] J. Reichel. *Microchip traps and Bose-Einstein condensation*. Appl. Phys. B **74**, 469–487 (2002).
- [50] R. Folman, P. Krüger, J. Schmiedmayer, J. Denschlag, and C. Henkel. *Microscopic atom optics: From wires to an atom chip*. Advances in Atomic, Molecular and Optical Physics **48**, 263–356 (2002).
- [51] J. Fortágh and C. Zimmermann. *Magnetic microtraps for ultracold atoms*. Rev. Mod. Phys. **79**, 235 (2007).
- [52] E. A. Hinds and I. G. Hughes. *Magnetic atom optics: mirrors, guides, traps, and chips for atoms*. J. Phys. D **32**, R119–R146 (1999).
- [53] S. Ghanbari, T. D. Kieu, A. Sidorov, and P. Hannaford. *Permanent magnetic lattices for ultracold atoms and quantum degenerate gases*. J. Phys. B **39**, 847–860 (2006).
- [54] R. Gerritsma, S. Whitlock, T. Fernholz, H. Schlatter, J. A. Luigjes, J.-U. Thiele, J. B. Goedkoop, and R. J. C. Spreeuw. *Lattice of microtraps for ultracold atoms based on patterned magnetic films*. Phys. Rev. A **76**(3), 033408 (2007).
- [55] S. Whitlock, R. Gerritsma, T. Fernholz, and R. J. C. Spreeuw. *Two-dimensional array of microtraps with atomic shift register on a chip*. arXiv **atom-ph**, 0803.2151v1 (2008).
- [56] P. Krüger, X. Luo, M. W. Klein, K. Brugger, A. Haase, S. Wildermuth, S. Groth, I. Bar-Joseph, R. Folman, and J. Schmiedmayer. *Trapping and manipulating neutral atoms with electrostatic fields*. Phys. Rev. Lett. **91**, 233201 (2003).
- [57] P. Horak, B. G. Klappauf, A. Haase, R. Folman, J. Schmiedmayer, P. Domokos, and E. A. Hinds. *Possibility of single-atom detection on a chip*. Phys. Rev. A **67**, 043806 (2003).

- [58] M. Wilzbach, A. Haase, M. Schwarz, D. Heine, K. Wicker, X. Liu, K.-H. Brenner, S. Groth, T. Fernholz, B. Hessmo, and J. Schmiedmayer. *Detecting neutral atoms on an atom chip*. Fortschr. Phys. **54**(8–10), 746–764 (2006).
- [59] I. Teper, Y.-J. Lin, and V. Vuletić. *Resonator-aided single-atom detection on a microfabricated chip*. Phys. Rev. Lett. **97**, 023002 (2006).
- [60] A. Takamizawa, T. Steinmetz, R. Delhuille, T. W. Hänsch, and J. Reichel. *Miniature fluorescence detector for single atom observation on a microchip*. Opt. Express **14**(23), 10976–10983 (2006).
- [61] T. P. Purdy and D. M. Stamper-Kurn. *Integrating cavity quantum electrodynamics and ultracold-atom chips with on-chip dielectric mirrors and temperature stabilization*. Appl. Phys. B **90**, 401–405 (2008).
- [62] S. Groth, P. Krüger, S. Wildermuth, R. Folman, T. Fernholz, D. Mahalu, I. Bar-Joseph, and J. Schmiedmayer. *Atom chips: Fabrication and thermal properties*. Appl. Phys. Lett. **85**, 2980–2982 (2004).
- [63] N. H. Dekker, C. S. Lee, V. Lorent, J. H. Thywissen, S. P. Smith, M. Drndić, R. M. Westervelt, and M. Prentiss. *Guiding neutral atoms on a chip*. Phys. Rev. Lett. **84**(6), 1124–1127 (2000).
- [64] J. Reichel, W. Hänsel, P. Hommelhoff, and T. W. Hänsch. *Applications of integrated magnetic microtraps*. Appl. Phys. B **72**, 81–89 (2001).
- [65] L. Della Pietra, S. Aigner, C. vom Hagen, S. Groth, I. Bar-Joseph, H. J. Lezec, and J. Schmiedmayer. *Designing potentials by sculpturing wires*. Phys. Rev. A **75**, 063604 (2007).
- [66] C. D. J. Sinclair, E. A. Curtis, I. L. Garcia, J. A. Retter, B. V. Hall, S. Eriksson, B. E. Sauer, and E. A. Hinds. *Bose-Einstein condensation on a permanent-magnet atom chip*. Phys. Rev. A **72**, 031603(R) (2005).
- [67] B. V. Hall, S. Whitlock, F. Scharnberg, P. Hannaford, and A. Sidorov. *A permanent magnetic film atom chip for Bose-Einstein condensation*. J. Phys. B **39**, 27–36 (2006).
- [68] I. Barb, R. Gerritsma, Y. Xing, J. Goedkoop, and R. Spreeuw. *Creating Ioffe-Pritchard micro-traps from permanent magnetic film with in-plane magnetization*. Eur. Phys. J. D **35**, 75–79 (2005).
- [69] M. Boyd, E. W. Streed, P. Medley, G. K. Campbell, J. Mun, W. Ketterle, and D. E. Pritchard. *Atom trapping with a thin magnetic film*. Phys. Rev. A **76**, 043624 (2007).
- [70] Y.-J. Lin, I. Teper, C. Chin, and V. Vuletić. *Impact of the Casimir-Polder potential and Johnson noise on Bose-Einstein condensate stability near surfaces*. Phys. Rev. Lett. **92**, 050404 (2004).

- [71] D. M. Harber, J. M. Obrecht, J. M. McGuirk, and E. A. Cornell. *Measurement of the Casimir-Polder force through center-of-mass oscillations of a Bose-Einstein condensate*. Phys. Rev. A **72**, 033610 (2005).
- [72] S. Hofferberth, I. Lesanovsky, B. Fischer, T. Schumm, and J. Schmiedmayer. *Non-equilibrium coherence dynamics in one-dimensional Bose gases*. Nature **449**, 324 (2007).
- [73] A. H. van Amerongen, J. J. P. van Es, P. Wicke, K. V. Kheruntsyan, and N. J. van Druten. *Yang-Yang thermodynamics on an atom chip*. Phys. Rev. Lett. **100**, 090402 (2008).
- [74] D. S. Petrov, G. V. Shlyapnikov, and J. T. M. Walraven. *Regimes of quantum degeneracy in trapped 1D gases*. Phys. Rev. Lett. **85**, 3745–3749 (2000).
- [75] J. Reichel and J. H. Thywissen. *Using magnetic chip traps to study Tonks-Girardeau quantum gases*. J. Phys. IV (France) **116**, 265–274 (2004).
- [76] B. Paredes, A. Widera, V. Murg, O. Mandel, S. Fölling, I. Cirac, G. V. Shlyapnikov, T. W. Hänsch, and I. Bloch. *Tonks-Girardeau gas of ultracold atoms in an optical lattice*. Nature **429**, 277–281 (2004).
- [77] T. Kinoshita, T. Wenger, and D. S. Weiss. *A quantum newton’s cradle*. Nature **440**, 900–903 (2006).
- [78] Y. Colombe, E. Knyazchyan, O. Morizot, B. Mercier, V. Lorent, and H. Perrin. *Ultracold atoms confined in rf-induced two-dimensional trapping potentials*. Europhys. Lett. **67**, 593–599 (2004).
- [79] T. Schumm, S. Hofferberth, L. M. Andersson, S. Wildermuth, S. Groth, I. Bar-Joseph, J. Schmiedmayer, and P. Krüger. *Matter-wave interferometry in a double well on an atom chip*. Nature Phys. **1**, 57–62 (2005).
- [80] S. Hofferberth, I. Lesanovsky, B. Fisher, J. Verdu, and J. Schmiedmayer. *Radio-frequency-dressed-state potentials for neutral atoms*. Nature Phys. **2**, 710–716 (2006).
- [81] M. White, H. Gao, M. Pasienski, and B. DeMarco. *Bose-Einstein condensates in rf-dressed adiabatic potentials*. Phys. Rev. A **74**, 023616 (2006).
- [82] G.-B. Jo, Y. Shin, S. Will, T. A. Pasquini, M. Saba, W. Ketterle, D. E. Pritchard, M. Vengalattore, and M. Prentiss. *Long phase coherence time and number squeezing of two Bose-Einstein condensates on an atom chip*. Phys. Rev. Lett. **98**(3), 030407 (2007).
- [83] G.-B. Jo, J.-H. Choi, C. Christensen, Y.-R. Lee, T. Pasquini, W. Ketterle, and D. Pritchard. *Matter-wave interferometry with phase fluctuating Bose-Einstein condensates*. Phys. Rev. Lett. **99**, 240406 (2007).

- [84] J. J. P. van Es, S. Whitlock, T. Fernholz, A. H. van Amerongen, and N. J. van Druten. *Longitudinal character of atom-chip-based rf-dressed potentials*. Phys. Rev. A **77**, 063623 (2008).
- [85] P. Treutlein, P. Hommelhoff, T. Steinmetz, T. W. Hänsch, and J. Reichel. *Coherence in microchip traps*. Phys. Rev. Lett. **92**, 203005 (2004).
- [86] T. Calarco, E. A. Hinds, D. Jaksch, J. Schmiedmayer, J. I. Cirac, and P. Zoller. *Quantum gates with neutral atoms: Controlling collisional interactions in time-dependent traps*. Phys. Rev. A **61**, 022304 (2000).
- [87] E. Charron, M. A. Cirone, A. Negretti, J. Schmiedmayer, and T. Calarco. *Theoretical analysis of a realistic atom-chip quantum gate*. Phys. Rev. A **74**, 012308 (2006).
- [88] A. H. van Amerongen. *One-dimensional Bose gas on an atom chip*. Ph.D. thesis, Universiteit van Amsterdam (2008).
- [89] T. Bergeman, G. Erez, and H. J. Metcalf. *Magnetostatic trapping fields for neutral atoms*. Phys. Rev. A **35**, 1535–1546 (1987).
- [90] W. H. Wing. *On neutral particle trapping in quasistatic electromagnetic fields*. Progress in Quantum Electronics **8**, 181–199 (1984).
- [91] S. Earnshaw. *On the nature of the molecular forces which regulate the constitution of the luminiferous ether*. Trans. Camb. Phil. Soc. **7**, 97–112 (1842).
- [92] W. Ketterle and D. E. Pritchard. *Trapping and focussing ground state atoms with static fields*. Appl. Phys. B **54**, 403–406 (1992).
- [93] R. Gerritsma and R. J. C. Spreeuw. *Topological constraints on magnetostatic traps*. Phys. Rev. A **74**, 043405 (2006).
- [94] E. Majorana. *Atomi orientati in campo magnetico variabile*. Nuovo Cimento **9**, 43–50 (1932).
- [95] C. V. Sukumar and D. M. Brink. *Spin-flip transitions in a magnetic trap*. Phys. Rev. A **56**(3), 2451–2454 (1997).
- [96] J. Luiten. *Lyman- $\alpha$  spectroscopy of magnetically trapped atomic hydrogen*. Ph.D. thesis, Universiteit van Amsterdam (1993).
- [97] D. J. Griffiths. *Introduction to electrodynamics, 3rd ed.* Prentice-Hall, 3 edition (1999).
- [98] S. Groth. *Development, fabrication and characterisation of atom chips*. Ph.D. thesis, University of Heidelberg (2006).
- [99] C. Aussibal. *Réalisation d'un condensat de Bose-Einstein sur une microstructure*. Ph.D. thesis, Institute d'optique, Université Paris XI (2003).



- [100] C. Cohen-Tannoudji, J. Dupont-Roc, and G. Grynberg. *Atom-Photon Interactions*. Wiley, New York (1992).
- [101] O. Zobay and B. M. Garraway. *Two-dimensional atom trapping in field-induced adiabatic potentials*. Phys. Rev. Lett. **86**, 1195–1198 (2001).
- [102] O. Zobay and B. M. Garraway. *Atom trapping and two-dimensional Bose-Einstein condensates in field-induced adiabatic potentials*. Phys. Rev. A **69**, 023605 (2004).
- [103] S. Hofferberth, I. Lesanovsky, T. Schumm, A. Imambekov, V. Gritsev, E. Demler, and J. Schmiedmayer. *Probing quantum and thermal noise in an interacting many-body system*. Nature Phys. **4**, 489–495 (2008).
- [104] D. E. Pritchard, K. Helmerson, and A. G. Martin. *Atom traps*. In S. Haroche, J. C. Gay, and G. Grynberg, editors, *Proceedings of the 11th International Conference on Atomic Physics*, 179–197. World Scientific, Singapore (1989).
- [105] O. J. Luiten, M. W. Reynolds, and J. T. M. Walraven. *Kinetic theory of the evaporative cooling of a trapped gas*. Phys. Rev. A **53**(1), 381–389 (1996).
- [106] J. Walraven. *Atomic hydrogen in magnetostatic traps*. In G.-L. Oppo, S. Barnett, E. Riis, and M. Wilkinson, editors, *Quantum dynamics of symple systems*, volume 44 of *SUSSP Proceedings*. IOP, Bristol (1996).
- [107] R. Eisberg and R. Resnick. *Quantum Physics of Atoms, Molecules, Solids, Nuclei, and Particles*. Wiley & Sons, New York (1985).
- [108] L. Allen and J. H. Eberly. *Optical resonance and two-level atoms*. Dover Publications, Inc, New York (1987).
- [109] S. Hofferberth. *Coherent manipulation of Bose-Einstein condensates with radio-frequency adiabatic potentials on atom chips*. Ph.D. thesis, University of Heidelberg (2007).
- [110] S. Hofferberth, B. Fischer, T. Schumm, J. Schmiedmayer, and I. Lesanovsky. *Ultracold atoms in radio-frequency dressed potentials beyond the rotating-wave approximation*. Phys. Rev. A **76**, 013401 (2007).
- [111] R. A. Cornelussen. *Optical trapping and manipulation of atoms near surfaces*. Ph.D. thesis, Universiteit van Amsterdam (2004).
- [112] M. Olshanii. *Atomic scattering in the presence of an external confinement and a gas of impenetrable bosons*. Phys. Rev. Lett. **81**, 938 (1998).
- [113] F. Gerbier. *Quasi-1D Bose-Einstein condensates in the dimensional crossover regime*. Europhys. Lett. **66**, 771–777 (2004).

- [114] J. Estève, C. Aussibal, T. Schumm, C. Figl, D. Mailly, I. Bouchoule, C. I. Westbrook, and A. Aspect. *The role of wire imperfections in micro magnetic traps for atoms*. Phys. Rev. A **70**, 043629 (2004).
- [115] J. Fortágh, H. Ott, G. Schlotterbeck, B. Herzog, D. Wharam, and C. Zimmermann. *Microelectromagnets for trapping and manipulating ultracold atomic quantum gases*. Appl. Phys. Lett. **81**, 1146 (2002).
- [116] J. Reichel, W. Hänsel, and T. W. Hänsch. *Atomic micromanipulation with magnetic surface traps*. Phys. Rev. Lett. **83**(17), 3398–3401 (1999).
- [117] *The Practical Application of Light*. Melles Griot (1999). Melles Griot product catalogue.
- [118] T. Gregorkiewicz. *private communication* (2008).
- [119] E. Nicollian and J. R. Brews. *MOS (Metal Oxide Semiconductor) Physics and Technology*. John Wiley & Sons, Inc., New York (1982).
- [120] H. Baker, editor. *Alloy Phase Diagrams*, volume 3 of *ASM Handbook*. ASM International, Materials Park, Ohio 44073-0002 (1992).
- [121] M. B. Squires. *High repetition rate Bose-Einstein condensate production in a compact, transportable vacuum system*. Ph.D. thesis, University of Colorado (2008).
- [122] S. Whitlock, B. V. Hall, T. Roach, R. Anderson, M. Volk, P. Hannaford, and A. I. Sidorov. *Effect of magnetization inhomogeneity on magnetic microtraps for atoms*. Phys. Rev. A **75**, 043602 (2007).
- [123] S. Kraft, A. Günther, H. Ott, D. Wharam, C. Zimmermann, and J. Fortágh. *Anomalous longitudinal magnetic field near the surface of copper conductors*. J. Phys. B **35**, L469–L474 (2002).
- [124] J. Fortágh, H. Ott, S. Kraft, and A. G. C. Zimmermann. *Surface effects in magnetic microtraps*. Phys. Rev. A **66**, 041604 (2002).
- [125] A. E. Leanhardt, A. P. Chikkatur, D. Kielpinski, Y. Shin, T. L. Gustavson, W. Ketterle, and D. E. Pritchard. *Propagation of Bose-Einstein condensates in a magnetic waveguide*. Phys. Rev. Lett. **89**, 040401 (2002).
- [126] A. E. Leanhardt, Y. Shin, A. P. Chikkatur, D. Kielpinski, W. Ketterle, and D. E. Pritchard. *Bose-Einstein condensates near a microfabricated surface*. Phys. Rev. Lett. **90**, 100404 (2003).
- [127] M. P. A. Jones, C. J. Vale, D. Sahagun, B. V. Hall, C. C. Eberlein, B. E. Sauer, K. Furusawa, D. Richardson, and E. A. Hinds. *Cold atoms probe the magnetic field near a wire*. J. Phys. B **37**, L15–L20 (2004).

- [128] C. J. Vale, B. Upcroft, M. J. Davis, N. R. Heckenberg, and H. Rubinsztein-Dunlop. *Foil-based atom chip for Bose-Einstein condensates*. J. Phys. B **37**, 2959–2967 (2004).
- [129] D.-W. Wang, M. D. Lukin, and E. Demler. *Disordered Bose-Einstein condensates in quasi one-dimensional magnetic microtraps*. Phys. Rev. Lett. **92**, 076802 (2004).
- [130] T. Schumm, J. Estève, C. Figl, J.-B. Trebbia, C. Aussibal, H. Nguyen, D. Mailly, I. Bouchoule, C. I. Westbrook, and A. Aspect. *Atom chips in the real world: the effects of wire corrugation*. Eur. Phys. J. D **32**, 171–180 (2005).
- [131] S. Wildermuth, S. Hofferberth, I. Lesanovsky, E. Haller, L. M. Andersson, S. Groth, I. Bar-Joseph, P. Krüger, and J. Schmiedmayer. *Microscopic magnetic-field imaging*. Nature **435**, 440 (2005).
- [132] S. Wildermuth, S. Hofferberth, I. Lesanovsky, S. Groth, P. Krüger, J. Schmiedmayer, and I. Bar-Joseph. *Sensing electric and magnetic fields with Bose-Einstein condensates*. Appl. Phys. Lett. **88**, 264103 (2006).
- [133] P. Krüger, L. M. Andersson, S. Wildermuth, S. Hofferberth, E. Haller, S. Aigner, S. Groth, I. Bar-Joseph, and J. Schmiedmayer. *Potential roughness near lithographically fabricated atom chips*. Phys. Rev. A **76**, 063621 (2007).
- [134] S. Aigner, L. Della Pietra, Y. Japha, O. Entin-Wohlman, T. David, R. Salem, R. Folman, and J. Schmiedmayer. *Long-range order in electronic transport through disordered metal films*. Science **319**, 1226–1229 (2008).
- [135] Y. Japha, O. Entin-Wohlman, T. David, R. Salem, S. Aigner, J. Schmiedmayer, and R. Folman. *Organized current patterns in disordered conductors*. arXiv **cond-mat**, 0803.4307v1 (2008).
- [136] E. Koukharenko, Z. Moktadir, M. Kraft, M. Abdelsalam, D. Bagnall, C. Vale, M. Jones, and E. Hinds. *Microfabrication of gold wires for atom guides*. Sensors and Actuators A **115**, 600–607 (2004).
- [137] J.-B. Trebbia, C. L. Garrido Alzar, R. Cornelussen, C. Westbrook, and I. Bouchoule. *Roughness suppression via rapid current modulation on an atom chip*. Phys. Rev. Lett. **98**, 263201 (2007).
- [138] I. Bouchoule, J.-B. Trebbia, and C. L. Garrido Alzar. *Limitation of the modulation method to smooth wire-guide roughness*. Phys. Rev. A **77**, 023624 (2008).
- [139] R. Matula. *Electrical resistivity of copper, gold, palladium, and silver*. Journal of Physical and Chemical Reference Data **8**, 1147–1298 (1979).

- [140] M. Trinker, S. Groth, S. Haslinger, S. Manz, T. Betz, I. Bar-Joseph, T. Schumm, and J. Schmiedmayer. *Multi-layer atom chips for versatile atom micro manipulation*. arXiv **physics**, 0801.3351v1 (2008).
- [141] M. H. T. Extavour, L. J. LeBlanc, T. Schumm, B. Cieslak, S. Myrskog, A. Stummer, S. Aubin, and J. H. Thywissen. *Dual-species quantum degeneracy of  $^{40}\text{K}$  and  $^{87}\text{Rb}$  on an atom chip*. In C. Roos, H. Häffner, and R. Blatt, editors, *Atomic Physics 20*, 241–249. AIP Conference Proceedings 869, New York (2006).
- [142] M. Drndić, K. S. Johnson, J. H. Thywissen, M. Prentiss, and R. M. Westervelt. *Micro-electromagnets for atom manipulation*. Appl. Phys. Lett. **72**, 2906 (1998).
- [143] R. C. Weast, editor. *Handbook of Chemistry and Physics, 53rd edition*. The Chemical Rubber Co., Cleveland, Ohio (1972).
- [144] G. A. Slack, R. A. Tanzilli, R. O. Pohl, and J. W. Vandersande. *The intrinsic thermal conductivity of AlN*. J. Phys. Chem. Solids **48**, 641–647 (1987).
- [145] *STE53NC50 datasheet*. STMicroelectronics (2002). <http://www.stm.com>.
- [146] E. Hennes. *Thermal properties of the atom chip assembly* (2006). Unpublished technical report.
- [147] Roper Scientific, 3440 East Britannia Drive, Tucson, Arizona 85706, U.S.A. *User Manual for CoolSNAP CF and CoolSNAP ES Systems* (2003). Rev. F0.
- [148] ViewPoint Systems, 800 West Metro Parkway, Rochester, NY 14623. *DIO-64 User Manual Intelligent Digital I/O System* (2003). Version 1.04.
- [149] National Instruments, 6504 Bridge Point Parkway, Austin, Texas 78730-5039, USA. *PCI/PXI-6711/6713 User Manual* (1998).
- [150] National Instruments, 11500 North Mopac Expressway, Austin, Texas 78759-3504, USA. *NI 6013/6014 User Manual* (2002).
- [151] Analog Devices, One Technology Way, P.O. Box 9106, Norwood, MA 02062-9106, U.S.A. *AD9854 CMOS 300 MSPS Quadrature Complete DDS* (2004). Rev. C.
- [152] O. Morizot, J. de Lapeyre de Bellair, F. Wiotte, O. Lopez, P.-E. Pottie, and H. Perrin. *Agile low phase noise radio-frequency sine wave generator applied to experiments on ultracold atoms*. arXiv **physics**, 0704.1974v1 (2007).
- [153] O. Morizot, L. Longchambon, R. Kollengode Easwaran, R. Dubessy, E. Knyazchyan, P.-E. Pottie, V. Lorent, and H. Perrin. *Influence of the radio-frequency source properties on rf-based atom traps*. Eur. Phys. J. D **47**, 209–214 (2008).

- [154] Y.-J. Wang, D. Z. Anderson, V. M. Bright, E. A. Cornell, Q. Diot, T. Kishimoto, M. Prentiss, R. A. Saravanan, S. R. Segal, and S. Wu. *Atom Michelson interferometer on a chip using a Bose-Einstein condensate*. Phys. Rev. Lett. **94**, 090405 (2005).
- [155] Y. Shin, C. Sanner, G.-B. Jo, T. A. Pasquini, M. Saba, W. Ketterle, D. E. Pritchard, M. Vengalattore, and M. Prentiss. *Interference of Bose-Einstein condensates split with an atom chip*. Phys. Rev. A **72**, 021604(R) (2005).
- [156] G.-B. Jo, J.-H. Choi, C. Christensen, T. Pasquini, Y.-R. Lee, W. Ketterle, and D. Pritchard. *Phase sensitive recombination of two Bose-Einstein condensates on an atom chip*. Phys. Rev. Lett. **98**, 180401 (2007).
- [157] M. P. A. Jones, C. J. Vale, D. Sahagun, B. V. Hall, and E. A. Hinds. *Spin coupling between cold atoms and the thermal fluctuations of a metal surface*. Phys. Rev. Lett. **91**, 080401 (2003).
- [158] A. Günther, M. Kemmler, S. Kraft, C. J. Vale, C. Zimmermann, and J. Fortágh. *Combined chips for atom optics*. Phys. Rev. A **71**, 063619 (2005).
- [159] B. V. Hall, S. Whitlock, R. Anderson, P. Hannaford, and A. I. Sidorov. *Condensate splitting in an asymmetric double well for atom chip based sensors*. Phys. Rev. Lett. **98**, 030402 (2007).
- [160] I. Lesanovsky, T. Schumm, S. Hofferberth, L. M. Andersson, P. Krüger, and J. Schmiedmayer. *Adiabatic radio-frequency potentials for the coherent manipulation of matter waves*. Phys. Rev. A **73**, 033619 (2006).
- [161] I. Lesanovsky, S. Hofferberth, J. Schmiedmayer, and P. Schmelcher. *Manipulation of ultracold atoms in dressed adiabatic radio-frequency potentials*. Phys. Rev. A **74**, 033619 (2006).
- [162] C. L. Garrido Alzar, H. Perrin, B. M. Garraway, and V. Lorent. *Evaporative cooling in a radio-frequency trap*. Phys. Rev. A **74**, 053413 (2006).
- [163] H. Ott, J. Fortágh, S. Kraft, A. Günther, D. Komma, and C. Zimmermann. *Nonlinear dynamics of a Bose-Einstein condensate in a magnetic waveguide*. Phys. Rev. Lett. **91**, 040402 (2003).
- [164] M. Antezza, L. P. Pitaevskii, and S. Stringari. *Effect of the Casimir-Polder force on the collective oscillations of a trapped Bose-Einstein condensate*. Phys. Rev. A **70**, 053619 (2004).
- [165] A. I. Sidorov, B. J. Dalton, S. M. Whitlock, and F. Scharnberg. *Asymmetric double-well potential for single-atom interferometry*. Phys. Rev. A **74**, 023612 (2006).
- [166] W. Guerin, J.-F. Riou, J. P. Gaebler, V. Josse, P. Bouyer, and A. Aspect. *Guided quasicontinuous atom laser*. Phys. Rev. Lett. **97**(20), 200402 (2006).

- [167] A. Messiah. *Quantum Mechanics*. North-Holland, Amsterdam (1961).
- [168] R. P. Feynman, R. B. Leighton, and M. Sands. *The Feynman Lectures on Physics*, volume III. Addison-Wesley Publishing Company (1965).
- [169] J. M. Cowley, editor. *Electron diffraction techniques*, volume 2. Oxford University Press, Oxford (1993).
- [170] E. Bauer. *Low energy electron microscopy*. Rep. Prog. Phys. **57**, 895–938 (1994).
- [171] D. B. Williams and C. B. Carter. *Transmission electron microscopy: A textbook for Materials Science*. Springer (1996).
- [172] H. Rauch and S. A. Werner. *Neutron Interferometry: Lessons in Experimental Quantum Mechanics*. Oxford University Press, Oxford (2000).
- [173] A. D. Cronin, J. Schmiedmayer, and D. E. Pritchard. *Atom interferometers*. arXiv **quant-ph**, 0712.3703v1 (2007).
- [174] M. R. Andrews, C. G. Townsend, H. J. Miesner, D. S. Durfee, D. M. Kurn, and W. Ketterle. *Observation of interference between two Bose condensates*. Science **275**, 637–641 (1997).
- [175] A. Miffre, M. Jacquoy, M. Büchner, G. Tréneç, and J. Vigué. *Atom interferometry*. Phys. Scr. **74**(2), C15–C23 (2006).
- [176] C. S. Adams, M. Sigel, and J. Mlynek. *Atom optics*. Physics Reports **240**(3), 143–210 (1994).
- [177] S. Altschuler and L. M. Franz. *Matter wave interferometric apparatus*. U. S. Patent No. 3,761,721 (1973).
- [178] O. Carnal and J. Mlynek. *Young’s double-slit experiment with atoms: A simple atom interferometer*. Phys. Rev. Lett. **66**, 2689–2692 (1991).
- [179] D. W. Keith, C. R. Ekstrom, Q. A. Turchette, and D. E. Pritchard. *An interferometer for atoms*. Phys. Rev. Lett. **66**(21), 2693–2696 (1991).
- [180] F. Riehle, T. Kisters, A. Witte, J. Helmcke, and C. J. Bordé. *Optical Ramsey spectroscopy in a rotating frame: Sagnac effect in a matter-wave interferometer*. Phys. Rev. Lett. **67**, 177–180 (1991).
- [181] M. Kasevich and S. Chu. *Atomic interferometry using stimulated Raman transitions*. Phys. Rev. Lett. **67**, 181–184 (1991).
- [182] A. Lenef, T. D. Hammond, E. T. Smith, M. S. Chapman, R. A. Rubenstein, and D. E. Pritchard. *Rotation sensing with an atom interferometer*. Phys. Rev. Lett. **78**(5), 760–763 (1997).

- [183] T. L. Gustavson, P. Bouyer, and M. A. Kasevich. *Precision rotation measurements with an atom interferometer gyroscope*. Phys. Rev. Lett. **78**(11), 2046–2049 (1997).
- [184] A. Peters, K. Y. Chung, B. Young, J. Hensley, and S. Chu. *Precision atom interferometry*. Phil. Trans. R. Soc. Lond. A **355**(1733), 2223–2233 (1997).
- [185] B. P. Anderson and M. Kasevich. *Macroscopic quantum interference from atomic tunnel arrays*. Science **282**, 1686 (1998).
- [186] S. Gupta, K. Dieckmann, Z. Hadzibabic, and D. E. Pritchard. *Contrast interferometry using Bose-Einstein condensates to measure  $h/m$  and  $\alpha$* . Phys. Rev. Lett. **89**(14), 140401 (2002).
- [187] M. S. Chapman, T. D. Hammond, A. Lenef, J. Schmiedmayer, R. A. Rubenstein, E. Smith, and D. E. Pritchard. *Photon scattering from atoms in an atom interferometer: Coherence lost and regained*. Phys. Rev. Lett. **75**, 3783–3787 (1995).
- [188] C. R. Ekstrom, J. Schmiedmayer, M. S. Chapman, T. D. Hammond, and D. E. Pritchard. *Measurement of the electric polarizability of sodium with an atom interferometer*. Phys. Rev. A **51**, 3883–3888 (1995).
- [189] Y. Shin, M. Saba, T. A. Pasquini, W. Ketterle, D. E. Pritchard, and A. E. Leanhardt. *Atom interferometry with Bose-Einstein condensates in a double-well potential*. Phys. Rev. Lett. **92**(5), 050405 (2004).
- [190] E. A. Hinds, C. J. Vale, and M. G. Boshier. *Two-wire waveguide and interferometer for cold atoms*. Phys. Rev. Lett. **86**, 1462–1465 (2001).
- [191] E. Altman and E. Demler. *Condensed-matter physics - relaxation after a tight squeeze*. Nature **449**, 296–297 (2007).
- [192] S. Du, M. B. Squires, Y. Imai, L. Czaia, R. A. Saravanan, V. Bright, J. Reichel, T. W. Hänsch, and D. Z. Anderson. *Atom-chip Bose-Einstein condensation in a portable vacuum cell*. Phys. Rev. A **70**, 053606 (2004).
- [193] C. Pethick and H. Smith. *Bose-Einstein Condensation in Dilute Gases*. Cambridge University Press, Cambridge (2002).
- [194] Y. Kagan, E. L. Surkov, and G. V. Shlyapnikov. *Evolution of a Bose-condensed gas under variations of the confining potential*. Phys. Rev. A **54**(3), R1753–R1756 (1996).
- [195] Y. Castin and R. Dum. *Bose-Einstein condensates in time dependent traps*. Phys. Rev. Lett. **77**(27), 5315–5319 (1996).
- [196] D. S. Petrov, G. V. Shlyapnikov, and J. T. M. Walraven. *Phase-fluctuating 3D Bose-Einstein condensates in elongated traps*. Phys. Rev. Lett. **87**, 050404 (2001).

- [197] D. S. Petrov, D. M. Gangardt, and G. V. Shlyapnikov. *Low-dimensional trapped gases*. J. Phys. IV (France) **116**, 5 (2004).
- [198] D. S. Petrov. *Bose-Einstein condensation in low-dimensional trapped gases*. Ph.D. thesis, Universiteit van Amsterdam (2003).
- [199] T. Schumm. *private communication* (2007).
- [200] I. Shvarchuck, C. Buggle, D. S. Petrov, K. Dieckmann, M. Zielonkowski, M. Kemmann, T. G. Tiecke, W. von Klitzing, G. V. Shlyapnikov, and J. T. M. Walraven. *Bose-Einstein condensation into nonequilibrium states studied by condensate focusing*. Phys. Rev. Lett. **89**, 270404 (2002).
- [201] I. Shvarchuck, C. Buggle, D. Petrov, and et al. *Focusing of Bose-Einstein condensates in free flight*. in: Interactions in ultracold gases, Wiley-VCH 415 (2003).
- [202] T. Schumm, P. Krüger, S. Hofferberth, I. Lesanovsky, S. Wildermuth, S. Groth, I. Bar-Joseph, L. M. Andersson, and J. Schmiedmayer. *A double well interferometer on an atom chip*. Quantum Information Processing **5**(6), 537–558 (2006).
- [203] A. Röhrli, M. Naraschewski, A. Schenzle, and H. Wallis. *Transition from phase locking to the interference of independent Bose condensates: Theory versus experiment*. Phys. Rev. Lett. **78**, 4143 (1997).
- [204] N. I. Fisher. *Statistical analysis of circular data*. Cambridge University Press (1993).
- [205] F. Gerbier, J. H. Thywissen, S. Richard, M. Hugbart, P. Bouyer, and A. Aspect. *Momentum distribution and correlation function of quasicondensates in elongated traps*. Phys. Rev. A **67**, 051602(R) (2003).