



Universiteit
Leiden
The Netherlands

Nuclear magnetic resonance force microscopy at millikelvin temperatures

Haan, A.M.J. den

Citation

Haan, A. M. J. den. (2016, March 9). *Nuclear magnetic resonance force microscopy at millikelvin temperatures*. Casimir PhD Series. Retrieved from <https://hdl.handle.net/1887/38444>

Version: Not Applicable (or Unknown)

License: [Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden](#)

Downloaded from: <https://hdl.handle.net/1887/38444>

Note: To cite this publication please use the final published version (if applicable).

Cover Page



Universiteit Leiden



The handle <http://hdl.handle.net/1887/38444> holds various files of this Leiden University dissertation

Author: Haan, Arthur den

Title: Nuclear magnetic resonance force microscopy at millikelvin temperatures

Issue Date: 2016-03-09

Bibliography

- [1] J. A. Sidles. “Noninductive detection of single-proton magnetic resonance”. *Applied Physics Letters*, vol. 58, pp. 2854–2856, 1991.
- [2] C. L. Degen, M. Poggio, H. J. Mamin, C. T. Rettner, and D. Rugar. “Nanoscale magnetic resonance imaging.” *Proc. Natl. Acad. Sci. U. S. A.*, vol. 106, no. 5, pp. 1313–7, 2009.
- [3] W. Kühlbrandt. “Cryo-EM enters a new era”. *Elife*, vol. 3, no. e03665, 2014.
- [4] R. McIntosh, D. Nicastro, and D. Mastronarde. “New views of cells in 3D: an introduction to electron tomography”. *Trends in Cell Biology*, vol. 15, no. 1, pp. 43 – 51, 2005.
- [5] J. C. Kendrew, G. Bodo, H. M. Dintzis, R. Parrish, H. Wyckoff, and D. C. Phillips. “A three-dimensional model of the myoglobin molecule obtained by x-ray analysis”. *Nature*, vol. 181, no. 4610, pp. 662–666, 1958.
- [6] H. M. Berman, J. Westbrook, Z. Feng, G. Gilliland, T. N. Bhat, H. Weissig, I. N. Shindyalov, and P. E. Bourne. “The Protein Data Bank”. *Nucleic Acids Res*, vol. 28, pp. 235–242, 2000.
- [7] Protein Data Bank, <http://www.rcsb.org>.
- [8] G. Scapin. “Structural biology and drug discovery”. *Current pharmaceutical design*, vol. 12, no. 17, pp. 2087–2097, 2006.
- [9] M. Congreve, C. W. Murray, and T. L. Blundell. “Keynote review: Structural biology and drug discovery”. *Drug discovery today*, vol. 10, no. 13, pp. 895–907, 2005.
- [10] V. Lounnas, T. Ritschel, J. Kelder, R. McGuire, R. P. Bywater, and N. Foloppe. “Current progress in structure-based rational drug design marks a new mindset in drug discovery”. *Computational and Structural Biotechnology Journal*, vol. 5, no. 6, pp. 1 – 14, 2013.
- [11] T. P. Knowles, M. Vendruscolo, and C. M. Dobson. “The physical basis of protein misfolding disorders”. *Physics today*, vol. 68, no. 3, p. 36, 2015.

- [12] J. P. Overington, B. Al-Lazikani, and A. L. Hopkins. “How many drug targets are there?” *Nat Rev Drug Discov*, vol. 5, no. 12, pp. 993–996, 2006.
- [13] Membrane proteins of known 3D structure,
<http://blanco.biomol.uci.edu/mpstruc/>.
- [14] J. J. Babcock and M. Li. “Deorphanizing the human transmembrane genome: A landscape of uncharacterized membrane proteins”. *Acta pharmacologica Sinica*, vol. 35, no. 1, pp. 11–23, 2014.
- [15] E. P. Carpenter, K. Beis, A. D. Cameron, and S. Iwata. “Overcoming the challenges of membrane protein crystallography”. *Current opinion in structural biology*, vol. 18, no. 5, pp. 581–586, 2008.
- [16] Y. Tao, J. Boss, B. Moores, and C. Degen. “Single-crystal diamond nanomechanical resonators with quality factors exceeding one million”. *Nature communications*, vol. 5, 2014.
- [17] A. Vinante, A. Kirste, A. den Haan, O. Usenko, G. Wijts, E. Jeffrey, P. Sonin, D. Bouwmeester, and T. H. Oosterkamp. “High sensitivity SQUID-detection and feedback-cooling of an ultrasoft microcantilever”. *Applied Physics Letters*, vol. 101, no. 12, 123101, 2012.
- [18] A. Abragam. *The Principles of Nuclear Magnetism*. pages: 363 (Ch. 1), 138–139 (Ch. 7), 66, 539–545 (Ch. 8) International series of monographs on physics. Clarendon Press, 1961.
- [19] S. Kuehn, S. A. Hickman, and J. A. Marohn. “Advances in mechanical detection of magnetic resonance”. *The Journal of Chemical Physics*, vol. 128, no. 5, 052208, 2008.
- [20] A. Vinante, G. Wijts, O. Usenko, L. Schinkelshoek, and T. H. Oosterkamp. “Magnetic resonance force microscopy of paramagnetic electron spins at millikelvin temperatures”. *Nature Communications*, vol. 2, 572, 2011.
- [21] J. M. de Voogd, J. J. T. Wagenaar, and T. H. Oosterkamp. “Dissipation and resonance frequency shift of a resonator magnetically coupled to a semiclassical spin”. 2015.
- [22] H. B. Callen and T. A. Welton. “Irreversibility and Generalized Noise”. *Phys. Rev.*, vol. 83, pp. 34–40, 1951.
- [23] H. J. Mamin, R. Budakian, B. W. Chui, and D. Rugar. “Detection and Manipulation of Statistical Polarization in Small Spin Ensembles”. *Phys. Rev. Lett.*, vol. 91, p. 207604, 2003.
- [24] B. Chui, Y. Hishinuma, R. Budakian, H. Mamin, T. Kenny, and D. Rugar. “Mass-loaded cantilevers with suppressed higher-order modes for magnetic resonance force microscopy”. In “TRANSDUCERS, Solid-State Sensors, Actuators and Microsystems, 12th International Conference on, 2003”, vol. 2, pp. 1120–1123. 2003.

- [25] H. C. Overweg, A. M. J. den Haan, H. J. Eerkens, P. F. A. Alkemade, A. L. La Rooij, R. J. C. Spreeuw, L. Bossoni, and T. H. Oosterkamp. “Probing the magnetic moment of FePt micromagnets prepared by focused ion beam milling”. *Applied Physics Letters*, vol. 107, no. 7, 072402, 2015.
- [26] G. H. C. J. Wijts. *Magnetic Resonance Force Microscopy at milliKelvin Temperatures*. pages: 13-39, 31, 87 (Ch. 2), 32-39 (Ch. 5), Ph.D. thesis, Leiden University, 2013.
- [27] D. Rugar, R. Budakian, H. J. Mamin, and B. W. Chui. “Single spin detection by magnetic resonance force microscopy”. *Nature*, vol. 430, no. 6997, pp. 329–332, 2004.
- [28] O. Usenko, A. Vinante, G. Wijts, and T. H. Oosterkamp. “A superconducting quantum interference device based read-out of a subattoNewton force sensor operating at millikelvin temperatures”. *Applied Physics Letters*, vol. 98, no. 13, 133105, 2011.
- [29] J. A. Marohn, R. Fainchtein, and D. D. Smith. “An optimal magnetic tip configuration for magnetic-resonance force microscopy of microscale buried features”. *Applied Physics Letters*, vol. 73, no. 25, 1998.
- [30] M. Poggio, C. L. Degen, C. T. Rettner, H. J. Mamin, and D. Rugar. “Nuclear magnetic resonance force microscopy with a microwire rf source”. *Applied Physics Letters*, vol. 90, no. 26, 263111, 2007.
- [31] K. Bastiaans. *Power dissipation of a type II superconducting microwire carrying large oscillating currents at low temperatures*. pages: 32,33 (ch. 2), 9-19, 37 (ch. 3) master thesis, Leiden University, 2015.
- [32] R. N. Kleiman, G. Agnolet, and D. J. Bishop. “Two-level systems observed in the mechanical properties of single-crystal silicon at low temperatures”. *Phys. Rev. Lett.*, vol. 59, pp. 2079–2082, 1987.
- [33] Z. Hao, A. Erbil, and F. Ayazi. “An analytical model for support loss in micromachined beam resonators with in-plane flexural vibrations”. *Sensors and Actuators A: Physical*, vol. 109, no. 12, pp. 156 – 164, 2003.
- [34] E. M. Chudnovsky and D. A. Garanin. “Damping of a nanocantilever by paramagnetic spins”. *Phys. Rev. B*, vol. 89, p. 174420, 2014.
- [35] D. Rugar, O. Zger, S. Hoen, C. S. Yannoni, H.-M. Vieth, and R. D. Kendrick. “Force Detection of Nuclear Magnetic Resonance”. *Science*, vol. 264, no. 5165, pp. 1560–1563, 1994.
- [36] S. Perisanu, P. Vincent, A. Ayari, M. Choueib, S. T. Purcell, M. Bechelany, and D. Cornu. “High Q factor for mechanical resonances of batch-fabricated SiC nanowires”. *Applied Physics Letters*, vol. 90, no. 4, 043113, 2007.

- [37] S. Perisanu, V. Gouttenoire, P. Vincent, A. Ayari, M. Choueib, M. Bechelany, D. Cornu, and S. T. Purcell. “Mechanical properties of SiC nanowires determined by scanning electron and field emission microscopies”. *Phys. Rev. B*, vol. 77, p. 165434, 2008.
- [38] T. R. Albrecht, P. Grutter, D. Horne, and D. Rugar. “Frequency modulation detection using highQ cantilevers for enhanced force microscope sensitivity”. *Journal of Applied Physics*, vol. 69, no. 2, 1991.
- [39] J. I. Kilpatrick, A. Gannepalli, J. P. Cleveland, and S. P. Jarvis. “Frequency modulation atomic force microscopy in ambient environments utilizing robust feedback tuning”. *Review of Scientific Instruments*, vol. 80, no. 2, 023701, 2009.
- [40] S. R. Garner, S. Kuehn, J. M. Dawlaty, N. E. Jenkins, and J. A. Marohn. “Force-gradient detected nuclear magnetic resonance”. *Applied Physics Letters*, vol. 84, no. 25, 2004.
- [41] L. Chen, J. G. Longenecker, E. W. Moore, and J. A. Marohn. “Long-lived frequency shifts observed in a magnetic resonance force microscope experiment following microwave irradiation of a nitroxide spin probe”. *Applied Physics Letters*, vol. 102, no. 13, 132404, 2013.
- [42] K. Kobayashi, H. Yamada, and K. Matsushige. “Frequency noise in frequency modulation atomic force microscopy”. *Review of Scientific Instruments*, vol. 80, no. 4, 043708, 2009.
- [43] Private communication with J.J.T. Wagenaar.
- [44] A. I. B. E. J. Clarke. *The SQUID Handbook, Vol. I Fundamentals and Technology of SQUIDs and SQUID Systems*. pages: 31-42, WILEY-VCH Verlag GmbH and Co. KGaA Weinheim, 2004.
- [45] W. P. Robins. *Phase Noise in Signal Sources: Theory and Applications*. pages: 20-26, Peter Peregrinus Ltd. IEE Telecommunications, 1984.
- [46] J. Kawamura, J. Chen, D. Miller, J. Kooi, J. Zmuidzinas, B. Bumble, H. G. LeDuc, and J. A. Stern. “Low-noise submillimeter-wave NbTiN superconducting tunnel junction mixers”. *Applied Physics Letters*, vol. 75, no. 25, 1999.
- [47] F. Crick and A. Hughes. “The physical properties of cytoplasm: A study by means of the magnetic particle method Part I. Experimental”. *Experimental Cell Research*, vol. 1, no. 1, pp. 37 – 80, 1950.
- [48] S. B. Smith, L. Finzi, and C. Bustamante. “Direct Mechanical Measurements of the Elasticity of Single DNA Molecules by Using Magnetic Beads”. *Science*, vol. 258, pp. 1122–1126, 1992.
- [49] J. G. Longenecker, H. Mamin, A. W. Senko, L. Chen, C. T. Rettner, D. Rugar, and J. A. Marohn. “High-gradient nanomagnets on cantilevers for sensitive detection of nuclear magnetic resonance”. *ACS nano*, vol. 6, no. 11, pp. 9637–9645, 2012.

- [50] A. I. Sidorov, R. J. McLean, B. A. Sexton, D. S. Gough, T. J. Davis, A. Akulushin, G. I. Opat, and P. Hannaford. “Structures magnétiques à l'échelle micronique pour l'optique atomique”. *Academie des Sciences Paris Comptes Rendus Serie Physique Astrophysique*, vol. 2, pp. 565–571, 2001.
- [51] S. Whitlock, R. Gerritsma, T. Fernholz, and R. J. C. Spreeuw. “Two-dimensional array of microtraps with atomic shift register on a chip”. *New Journal of Physics*, vol. 11, no. 2, p. 023021, 2009.
- [52] T. J. Davis. “Atomic de Broglie waveguides and integrated atom-optics using permanent magnets”. *Journal of Optics B: Quantum and Semiclassical Optics*, vol. 1, pp. 408–414, 1999.
- [53] Y. T. Xing, A. Eljaouhari, I. Barb, R. Gerritsma, R. J. C. Spreeuw, and J. B. Goedkoop. “Hard magnetic FePt films for atom chips”. *Physica Status Solidi C Current Topics*, vol. 1, pp. 3702–3705, 2004.
- [54] Y. T. Xing, I. Barb, R. Gerritsma, R. J. C. Spreeuw, H. Luigjes, Q. F. Xiao, C. Rétif, and J. B. Goedkoop. “Fabrication of magnetic atom chips based on FePt”. *Journal of Magnetism and Magnetic Materials*, vol. 313, pp. 192–197, 2007.
- [55] 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*, vol. 76, no. 3, 033408, 2007.
- [56] V. Y. F. Leung, D. R. M. Pijn, H. Schlatter, L. Torralbo-Campo, A. L. La Rooij, G. B. Mulder, J. Naber, M. L. Soudijn, A. Tauschinsky, C. Abarbanel, B. Hadad, E. Golan, R. Folman, and R. J. C. Spreeuw. “Magnetic-film atom chip with $10\ \mu\text{m}$ period lattices of microtraps for quantum information science with Rydberg atoms”. *Review of Scientific Instruments*, vol. 85, no. 5, 053102, 2014.
- [57] S. Jose, P. Surendran, Y. Wang, I. Herrera, L. Krzemien, S. Whitlock, R. McLean, A. Sidorov, and P. Hannaford. “Periodic array of Bose-Einstein condensates in a magnetic lattice”. *Phys. Rev. A*, vol. 89, no. 5, 051602, 2014.
- [58] M. Poggio and C. Degen. “Force-detected nuclear magnetic resonance: recent advances and future challenges”. *Nanotechnology*, vol. 21, no. 34, p. 342001, 2010.
- [59] B. C. Stipe, H. J. Mamin, T. D. Stowe, T. W. Kenny, and D. Rugar. “Magnetic Dissipation and Fluctuations in Individual Nanomagnets Measured by Ultra-sensitive Cantilever Magnetometry”. *Physical Review Letters*, vol. 86, p. 2874, 2001.
- [60] N. E. Jenkins. “Batch fabrication and characterization of ultrasensitive cantilevers with submicron magnetic tips”. *Journal of Vacuum Science Technology B: Microelectronics and Nanometer Structures*, vol. 22, p. 909, 2004.

- [61] S. Rubanov and P. R. Munroe. “FIB-induced damage in silicon”. *Journal of Microscopy*, vol. 214, no. 3, pp. 213–221, 2004.
- [62] L. Giannuzzi and F. Stevie. “A review of focused ion beam milling techniques for TEM specimen preparation”. *Micron*, vol. 30, no. 3, pp. 197 – 204, 1999.
- [63] C. Rossel, P. Bauer, D. Zech, J. Hofer, M. Willemin, and H. Keller. “Active microlevers as miniature torque magnetometers”. *Journal of Applied Physics*, vol. 79, pp. 8166–8173, 1996.
- [64] W. K. Shen, J. H. Judy, and J.-P. Wang. “In situ epitaxial growth of ordered FePt (001) films with ultra small and uniform grain size using a RuAl underlayer”. *Journal of Applied Physics*, vol. 97, no. 10, 10H301, 2005.
- [65] E. C. Heeres, A. J. Katan, M. H. van Es, A. F. Beker, M. Hesselberth, D. J. van der Zalm, and T. H. Oosterkamp. “A compact multipurpose nanomanipulator for use inside a scanning electron microscope”. *Review of Scientific Instruments*, vol. 81, no. 2, p. 023704, 2010.
- [66] J. P. Attané, D. Ravelosona, A. Marty, V. D. Nguyen, and L. Vila. “Coercivity enhancement in FePt nanowires due to the suppression of available paths for domain wall propagation”. *Phys. Rev. B*, vol. 84, p. 144418, 2011.
- [67] J. P. Cleveland, S. Manne, D. Bocek, and P. K. Hansma. “A nondestructive method for determining the spring constant of cantilevers for scanning force microscopy”. *Review of Scientific Instruments*, vol. 64, pp. 403–405, 1993.
- [68] T. N. Ng, N. E. Jenkins, and J. A. Marohn. “Thermomagnetic fluctuations and hysteresis loops of magnetic cantilevers for magnetic resonance force microscopy”. *IEEE Transactions on Magnetics*, vol. 42, pp. 378–381, 2006.
- [69] C. Hammel, private communication.
- [70] R. Gerritsma. *Permanent magnetic atom chips and Bose-Einstein condensation*. Ph.D. thesis, Universiteit van Amsterdam, 2007.
- [71] V. Leung, A. Tauschinsky, N. van Druten, and R. Spreeuw. “Microtrap arrays on magnetic film atom chips for quantum information science”. *Quantum Information Processing*, vol. 10, no. 6, pp. 955–974, 2011.
- [72] I. Herrera, Y. Wang, P. Michaux, D. Nissen, P. Surendran, S. Juodkazis, S. Whitlock, R. J. McLean, A. Sidorov, M. Albrecht, and P. Hannaford. “Sub-micron period lattice structures of magnetic microtraps for ultracold atoms on an atom chip”. *Journal of Physics D Applied Physics*, vol. 48, no. 11, 115002, 2015.
- [73] K. Uhlig. “Cryogen-free dilution refrigerators”. *Nature*, vol. 485, no. 5, p. 052039, 2012.
- [74] W. J. Nuttal, R. H. Clarke, and B. A. Glowacki. “Resources: Stop squandering helium”. *Journal of Physics: Conference Series*, vol. 400, no. 7400, pp. 573–575, 2012.

- [75] S. H. Pan, E. W. Hudson, and J. C. Davis. “3He refrigerator based very low temperature scanning tunneling microscope”. *Review of Scientific Instruments*, vol. 70, no. 2, pp. 1459–1463, 1999.
- [76] J. Wiebe, A. Wachowiak, F. Meier, D. Haude, T. Foster, M. Morgenstern, and R. Wiesendanger. “A 300mK ultra-high vacuum scanning tunneling microscope for spin-resolved spectroscopy at high energy resolution”. *Review of Scientific Instruments*, vol. 75, no. 11, pp. 4871–4879, 2004.
- [77] E. Tartaglini, T. G. A. Verhagen, F. Galli, M. L. Trouwborst, R. Mller, T. Shioota, J. Aarts, and J. M. van Ruitenbeek. “New directions in point-contact spectroscopy based on scanning tunneling microscopy techniques (Review Article)”. *Low Temperature Physics*, vol. 39, no. 3, pp. 189–198, 2013.
- [78] Y. J. Song, A. F. Otte, V. Shvarts, Z. Zhao, Y. Kuk, S. R. Blankenship, A. Band, F. M. Hess, and J. A. Stroscio. “Invited Review Article: A 10 mK scanning probe microscopy facility”. *Review of Scientific Instruments*, vol. 81, no. 12, 121101, 2010.
- [79] Cryomech. *Cryogenic Refrigerator manual*.
- [80] A. Waele. “Basic Operation of Cryocoolers and Related Thermal Machines”. *Journal of Low Temperature Physics*, vol. 164, no. 5-6, pp. 179–236, 2011.
- [81] M. Pelliccione, A. Sciambi, J. Bartel, A. J. Keller, and D. Goldhaber-Gordon. “Design of a scanning gate microscope for mesoscopic electron systems in a cryogen-free dilution refrigerator”. *Review of Scientific Instruments*, vol. 84, no. 3, 033703, 2013.
- [82] Leiden Cryogenics, CF-650, Leiden, The Netherlands.
- [83] Cryomech, PT415, Syracuse, NY.
- [84] F. Pobell. *Matter and Methods at Low Temperatures*, p. pages: 225 (Ch. 6). Springer, 3rd ed., 2007.
- [85] K. Uhlig. “3He/4He dilution refrigerator with pulse-tube refrigerator precooling”. *Cryogenics*, vol. 42, no. 2, pp. 73 – 77, 2002.
- [86] Amatec, E0360-055-3500S, Alphen aan den Rijn, The Netherlands.
- [87] O. Usenko. *Development and testing of the gravitational wave antenna Mini-GRAIL in its full-featured configuration*. Ph.D. thesis, Leiden University, 2012.
- [88] Geospace Technologies, GS11D, Houston, Texas.
- [89] S. Kelly. *Complex Oxides Studied by Scanning Tunneling Microscopy/Spectroscopy*. Ph.D. thesis, Leiden University, 2012.
- [90] S. Pan. “Piezoelectric motor”, 1993. WO Patent App. PCT/GB1993/000,539.
- [91] PhysikInstrument, P-142.10, Karlsruhe, Germany.

- [92] Leiden Probe Microscopy, LPM, Video Rate SPM Control Electronics, Leiden, The Netherlands.
- [93] Hightech Development Leiden, HDL, SRD1000 sensor and CMN1000 sensor, Leiden, The Netherlands.
- [94] S. Hembacher, F. J. Giessibl, J. Mannhart, and C. F. Quate. “Revealing the hidden atom in graphite by low-temperature atomic force microscopy”. *Proceedings of the National Academy of Sciences*, vol. 100, no. 22, pp. 12539–12542, 2003.
- [95] A. M. J. Den Haan, G. H. C. J. Wijts, F. Galli, O. Usenko, G. J. C. Van Baarle, D. J. Van Der Zalm, and T. H. Oosterkamp. “Atomic resolution scanning tunneling microscopy in a cryogen free dilution refrigerator at 15 mK”. *Rev. Sci. Instrum.*, vol. 85, no. 3, p. 035112, 2014.
- [96] Leiden Spin Imaging, LSI, Leiden, The Netherlands.
- [97] A. M. J. den Haan, J. J. T. Wagenaar, J. M. de Voogd, G. Koning, and T. H. Oosterkamp. “Spin-mediated dissipation and frequency shifts of a cantilever at milliKelvin temperatures”. *Phys. Rev. B*, vol. 92, p. 235441, 2015.
- [98] S. Kuehn, R. F. Loring, and J. A. Marohn. “Dielectric fluctuations and the origins of noncontact friction”. *Phys. Rev. Lett.*, vol. 96, no. 15, p. 156103, 2006.
- [99] B. C. Stipe, H. J. Mamin, T. D. Stowe, T. W. Kenny, and D. Rugar. “Magnetic dissipation and fluctuations in individual nanomagnets measured by ultrasensitive cantilever magnetometry”. *Phys. Rev. Lett.*, vol. 86, no. 13, pp. 2874–2877, 2001.
- [100] J. G. E. Harris, R. Knobel, K. D. Maranowski, A. C. Gossard, N. Samarth, and D. D. Awschalom. “Damping of micromechanical structures by paramagnetic relaxation”. *Appl. Phys. Lett.*, vol. 82, no. 20, pp. 3532–3534, 2003.
- [101] D. Rugar, H. J. Mamin, P. Guethner, S. E. Lambert, J. E. Stern, I. McFadyen, and T. Yogi. “Magnetic force microscopy: General principles and application to longitudinal recording media”. *J. Appl. Phys.*, vol. 68, no. 3, pp. 1169–1183, 1990.
- [102] R. P. Taylor, G. F. Nellis, S. A. Klein, D. W. Hoch, J. Fellers, P. Roach, J. M. Park, and Y. Gianchandani. “Measurements of the Material Properties of a Laminated Piezoelectric Stack at Cryogenic Temperatures”. In “Advances in Cryogenic Engineering”, vol. 824, pp. 200–207. AIP Publishing, 2006.
- [103] D. Haneman. “Electron paramagnetic resonance from clean single-crystal cleavage surfaces of silicon”. *Phys. Rev.*, vol. 170, no. 3, pp. 705–718, 1968.
- [104] B. P. Lemke and D. Haneman. “Low-Temperature EPR Measurements on *in situ* Vacuum-Cleaved Silicon”. *Phys. Rev. Lett.*, vol. 35, pp. 1379–1382, 1975.

- [105] T. Rosskopf, A. Dussaux, K. Ohashi, M. Loretz, R. Schirhagl, H. Watanabe, S. Shikata, K. M. Itoh, and C. L. Degen. “Investigation of surface magnetic noise by shallow spins in diamond”. *Phys. Rev. Lett.*, vol. 112, no. 14, p. 147602, 2014.
- [106] D. A. Alexson, S. A. Hickman, J. A. Marohn, and D. D. Smith. “Single-shot nuclear magnetization recovery curves with force-gradient detection”. *Applied Physics Letters*, vol. 101, no. 2, 022103, 2012.
- [107] A. Abragam. *Principles of Nuclear Magnetism*. 1961.
- [108] C. Slichter. *Principles of Magnetic Resonance*. pages: 12-21 (Ch. 8), Springer Series in Solid-State Sciences. Springer Berlin Heidelberg, 1996.
- [109] J. M. de Voogd, J. J. T. Wagenaar, and T. H. Oosterkamp. “Dissipation and resonance frequency shift of a resonator magnetically coupled to a semiclassical spin”. *ArXiv e-prints*, 2015.
- [110] A. Suter, M. Mali, J. Roos, and D. Brinkmann. “Mixed magnetic and quadrupolar relaxation in the presence of a dominant static Zeeman Hamiltonian”. *Journal of Physics: Condensed Matter*, vol. 10, no. 26, p. 5977, 1998.
- [111] O. Louasmaa. *Experimental principles and methods below 1 K*. Academic Press, 1974.
- [112] M. Huiku, T. Jyrkkio, J. Kyynarainen, M. Loponen, O. Louasmaa, and A. Oja. “Investigations of nuclear antiferromagnetic ordering in copper at nanokelvin temperatures”. *Journal of Low Temperature Physics*, vol. 62, no. 5-6, pp. 433–487, 1986.
- [113] A. Oja and O. Louasmaa. “Nuclear magnetic ordering in simple metals at positive and negative nanokelvin temperatures”. *Reviews of Modern Physics*, vol. 69, no. 1, p. p. 14, 1997.
- [114] N. Bloembergen. “On the interaction of nuclear spins in a crystalline lattice”. *Physica*, vol. 15, no. 34, pp. 386 – 426, 1949.
- [115] G. P. Berman, B. M. Chernobrod, V. N. Gorshkov, and V. I. Tsifrinovich. “Spin diffusion and relaxation in a nonuniform magnetic field”. *Phys. Rev. B*, vol. 71, p. 184409, 2005.
- [116] C. Kittel. *Introduction to Solid State Physics*. John Wiley & Sons, Inc., New York, 6th ed., 1986.
- [117] A. Tannús, M. Garwood, et al. “Adiabatic pulses”. *NMR in Biomedicine*, vol. 10, no. 8, pp. 423–434, 1997.
- [118] F. Bloch. “Nuclear Induction”. *Phys. Rev.*, vol. 70, pp. 460–474, 1946.
- [119] A. G. Redfield. “Nuclear magnetic resonance saturation and rotary saturation in solids”. *Physical Review*, vol. 98, no. 6, p. 1787, 1955.

- [120] J. Baum, R. Tycko, and A. Pines. “Broadband and adiabatic inversion of a two-level system by phase-modulated pulses”. *Phys. Rev. A*, vol. 32, pp. 3435–3447, 1985.
- [121] Ē. Kupce and R. Freeman. “Stretched adiabatic pulses for broadband spin inversion”. *Journal of Magnetic Resonance, Series A*, vol. 117, no. 2, pp. 246–256, 1995.
- [122] T. Oosterkamp, M. Poggio, C. Degen, H. Mamin, and D. Rugar. “Frequency domain multiplexing of force signals with application to magnetic resonance force microscopy”. *Applied Physics Letters*, vol. 96, no. 8, p. 083107, 2010.
- [123] M. Garwood and Y. Ke. “Symmetric pulses to induce arbitrary flip angles with compensation for RF inhomogeneity and resonance offsets”. *Journal of Magnetic Resonance (1969)*, vol. 94, no. 3, pp. 511–525, 1991.
- [124] B. Stipe, H. Mamin, C. Yannoni, T. Stowe, T. Kenny, and D. Rugar. “Electron spin relaxation near a micron-size ferromagnet”. *Physical review letters*, vol. 87, no. 27, p. 277602, 2001.
- [125] D. Rugar, C. Yannoni, and J. Sidles. “Mechanical detection of magnetic resonance”. *Nature*, vol. 360, no. 6404, pp. 563–566, 1992.
- [126] K. Wago, D. Botkin, C. S. Yannoni, and D. Rugar. “Force-detected electron-spin resonance: Adiabatic inversion, nutation, and spin echo”. *Phys. Rev. B*, vol. 57, pp. 1108–1114, 1998.
- [127] WebElements, <http://www.webelements.com/>.
- [128] P. Bhattacharya, R. Fornari, and H. Kamimura. *Comprehensive Semiconductor Science and Technology, Six-Volume Set: Online version*. page: 427. Elsevier Science, 2011.