



Universiteit
Leiden
The Netherlands

Advances in SQUID-detected magnetic resonance force microscopy

Wit, M. de

Citation

Wit, M. de. (2019, June 18). *Advances in SQUID-detected magnetic resonance force microscopy*. *Casimir PhD Series*. Retrieved from <https://hdl.handle.net/1887/74054>

Version: Not Applicable (or Unknown)

License: [Leiden University Non-exclusive license](#)

Downloaded from: <https://hdl.handle.net/1887/74054>

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

Cover Page



Universiteit Leiden



The handle <http://hdl.handle.net/1887/74054> holds various files of this Leiden University dissertation.

Author: Wit, M. de

Title: Advances in SQUID-detected magnetic resonance force microscopy

Issue Date: 2019-06-18

ADVANCES IN SQUID-DETECTED
MAGNETIC RESONANCE FORCE
MICROSCOPY

PROEFSCHRIFT

TER VERKRIJGING VAN
DE GRAAD VAN DOCTOR AAN DE UNIVERSITEIT LEIDEN,
OP GEZAG VAN RECTOR MAGNIFICUS PROF. MR. C.J.J.M STOLKER,
VOLGENS BESLUIT VAN HET COLLEGE VOOR PROMOTIES
TE VERDEDIGEN OP DINSDAG 18 JUNI 2019
KLOKKE 15:00 UUR

DOOR

MARTIN DE WIT

GEBOREN TE KATWIJK AAN ZEE
IN 1991

Promotor: Prof. dr. ir. T.H. Oosterkamp

Promotiecommissie: Dr. J.P. Davis (University of Alberta, Edmonton, Canada)
Prof. dr. J.A. Marohn (Cornell University, Ithaca, USA)
Prof. dr. E.R. Eliel
Dr. M.I. Huber
Prof. dr. J.M. van Ruitenbeek

Casimir PhD Series, Delft-Leiden 2019-14

ISBN 978-90-8593-400-4

An electronic version of this thesis can be found at <https://openaccess.leidenuniv.nl>

The work described in this thesis was performed at the Huygens - Kamerlingh Onnes Laboratory, Leiden University, Niels Bohrweg 2, 2333 CA, Leiden.

This research is funded by the Netherlands Organisation for Scientific Research (NWO).

The cover shows an abstract illustration of the mechanical vibration isolation, one of the main achievements of this research resulting from the close collaboration between the scientists and technicians in our lab. *Designed by Ilse Modder, www.ilsemodder.nl*

Copyright © 2019 Martin de Wit
Printed by: Gildeprint - Enschede

CONTENTS

1	Introduction	1
1.1	Development and applications of MRFM	2
1.2	Principles of MRFM	4
1.3	Sensitivity limit and the Oosterkamp approach	6
1.4	Thesis Outline	8
2	Instrumentation: Fermat and Yeti	11
2.1	Introduction.	12
2.2	MRFM detection chip	13
2.3	Cantilever	18
2.4	Fermat	21
2.5	Cryostat Yeti	32
3	Vibration isolation with high thermal conductance for a cryogen-free dilution refrigerator	37
3.1	Introduction.	38
3.2	Filter design.	39
3.3	Practical design and implementation	43
3.4	Experimental results	47
3.5	Conclusions	54
4	Feasibility of imaging in nuclear Magnetic Resonance Force Microscopy using Boltzmann polarization	57
4.1	Introduction.	58
4.2	Methods.	59
4.3	Frequency shifts measured in copper	67
4.4	Demonstration of volume sensitivity.	70
4.5	Imaging protons	72
4.6	Conclusions	76
4.7	Relevant NMR parameters of copper	77
4.8	Spin diffusion length for copper	77

5	Density and T_1 of surface and bulk spins in diamond in high magnetic field gradients	79
5.1	Introduction.	80
5.2	Methods.	81
5.3	Results and discussion	87
5.4	Summary and outlook	91
5.5	Vacuum properties of the cantilever	93
5.6	Fits with constant T_1 times	94
6	Flux compensation for SQUID-detected Magnetic Resonance Force Microscopy	95
6.1	Introduction.	96
6.2	Circuit and calibration	98
6.3	Results	101
6.4	Conclusions and outlook	103
7	Dissipation of the alternating magnetic field source	105
7.1	Introduction.	106
7.2	Calorimetry at mK temperatures	106
7.3	Characterization of dissipation.	110
7.4	Models for the origin of dissipation	113
7.5	Suggestions to reduce dissipation	120
7.6	Reducing the effects of dissipation.	121
7.7	Conclusions	122
8	Double-magnet cantilevers for increased magnetic field gradients	125
8.1	Introduction.	126
8.2	Intuition about magnetic field gradients.	127
8.3	Signal-to-noise ratio	129
8.4	Fabrication of double-magnet cantilevers	130
8.5	Magnetic field distribution	132
8.6	Enhanced coupling strength to pickup loop.	134
8.7	Spin-induced dissipation	135
8.8	Conclusions	139
9	Valorisation: the easy-MRFM	141
9.1	Necessity for a new characterization tool	142
9.2	Progress of the easy-MRFM	143
9.3	Future applications	146

A	Feedback cooling of the cantilever’s fundamental mode	147
A.1	Cantilever temperature and thermal noise force	148
A.2	Feedback cooling of the cantilever’s fundamental mode	151
B	Limitations of the mechanical generation of radio-frequency fields	155
B.1	Off-resonant coupling.	156
B.2	Non-linearities	158
B.3	Temperature dependence of quality factor	158
C	Quenching of SQUID modulation under radio-frequency interference	161
C.1	Quenched SQUID modulation	162
C.2	Possibilities	163
D	Fabrication recipes	165
D.1	Detection chip	166
D.2	Double layer resists for sputtering	167
D.3	Specific samples.	169
D.4	Considerations for double-layer detection chips	170
	Bibliography	173
	Samenvatting	193
	Curriculum Vitae	201
	List of Publications	203
	Acknowledgements	205

