



## Interplay of proximity effects in superconductor / ferromagnet heterostructures

Annika Stellhorn

Schlüsseltechnologien / Key Technologies  
Band / Volume 242  
ISBN 978-3-95806-562-8

Forschungszentrum Jülich GmbH  
Jülich Centre for Neutron Science (JCNS)  
Quantenmaterialien und kollektive Phänomene (JCNS-2/PGI-4)

## **Interplay of proximity effects in superconductor/ferromagnet heterostructures**

Annika Stellhorn

Schriften des Forschungszentrums Jülich  
Reihe Schlüsseltechnologien / Key Technologies

Band / Volume 242

---

ISSN 1866-1807

ISBN 978-3-95806-562-8

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>Superconductor-Ferromagnet Interactions</b>	<b>5</b>
2.1	Ferromagnetism . . . . .	5
2.1.1	Basics of ferromagnetism . . . . .	5
2.1.2	Magnetic anisotropy . . . . .	6
2.1.3	Domain formation and closure domains in FePd thin films . . . . .	10
2.2	Superconductivity . . . . .	11
2.2.1	Microscopic theory . . . . .	11
2.2.2	Ginzburg-Landau theory . . . . .	14
2.2.3	Dirty superconductors . . . . .	17
2.2.4	Small superconductors . . . . .	18
2.2.5	Magnetization of type-II superconductors . . . . .	22
2.2.6	Nb thin films . . . . .	23
2.3	Proximity effects in S/N structures . . . . .	26
2.4	Proximity effects in S/F structures . . . . .	27
2.4.1	Domain-superconductivity . . . . .	32
2.4.2	Long-range proximity effects . . . . .	36
2.4.2.1	Applications . . . . .	39
<b>3</b>	<b>Neutron scattering theory</b>	<b>43</b>
3.1	Basics on scattering theory . . . . .	43
3.2	Reflectometry on thin film heterostructures . . . . .	48
3.2.1	Specular reflectometry . . . . .	50
3.2.2	Off-specular scattering . . . . .	53
3.2.3	Magnetic reflectometry and off-specular scattering . . . . .	56

## CONTENTS

---

3.2.4	Simulation of GISANS measurements on thin film FePd . . . . .	58
<b>4</b>	<b>Experimental methods</b>	<b>61</b>
4.1	Molecular Beam Epitaxy . . . . .	61
4.1.1	Basic growth mechanisms . . . . .	62
4.1.2	MBE-Setup . . . . .	63
4.2	In-situ characterization methods . . . . .	65
4.2.1	Reflection High-Energy Electron Diffraction . . . . .	65
4.2.2	Low-Energy Electron Diffraction . . . . .	67
4.3	Ex-situ characterization methods . . . . .	68
4.3.1	X-Ray Reflectometry and Diffractometry . . . . .	69
4.3.2	Scanning Transmission Electron Microscopy . . . . .	69
4.3.3	Rutherford Backscattering Spectrometry . . . . .	71
4.3.4	Atomic and Magnetic Force Microscopy . . . . .	71
4.3.5	Magnetic Properties Measurement System . . . . .	73
4.3.6	Physical Properties Measurement System . . . . .	74
4.3.7	Large scale facility instruments . . . . .	74
4.3.7.1	GALAXI . . . . .	75
4.3.7.2	KWS-3 . . . . .	75
4.3.7.3	vSANS . . . . .	76
<b>5</b>	<b>Growth and room temperature characterization</b>	<b>79</b>
5.1	FePd in the L <sub>1</sub> <sub>0</sub> -phase . . . . .	79
5.2	FePd with varying PMA . . . . .	81
5.3	Sample growth . . . . .	82
5.3.1	Growth procedure . . . . .	84
5.3.2	Growth of FePd with high, low, and medium PMA . . . . .	86
5.3.3	In-situ characterization . . . . .	86
5.4	Ex-situ characterization . . . . .	90
5.4.1	X-ray reflectometry and diffractometry . . . . .	90
5.4.2	Surface analysis . . . . .	94
5.4.3	Magnetic domain structure and macroscopic magnetization . . . . .	96
5.4.4	GISANS at room temperature . . . . .	100
5.5	Conclusions . . . . .	104
<b>6</b>	<b>Low-temperature characterization</b>	<b>107</b>
6.1	Coexistence of superconductivity and ferromagnetism . . . . .	108
6.2	Magnetotransport with out-of-plane magnetic field . . . . .	110

---

## CONTENTS

6.2.1	High PMA . . . . .	111
6.2.2	Comparison of PMA . . . . .	118
6.3	Magnetotransport with in-plane magnetic field . . . . .	123
6.3.1	Low PMA . . . . .	123
6.3.2	Comparison of PMA . . . . .	128
6.4	Conclusions . . . . .	128
<b>7</b>	<b>Neutron scattering results of high-PMA Nb/FePd</b>	<b>131</b>
7.1	Temperature dependence . . . . .	131
7.2	Vector magnetization . . . . .	134
7.2.1	Results at $T > T_c$ . . . . .	142
7.2.2	Results at $T < T_c$ . . . . .	144
7.3	Conclusions . . . . .	147
<b>8</b>	<b>Conclusion and outlook</b>	<b>149</b>
8.1	Summary of room- and low-temperature results . . . . .	149
8.2	Scope of future work . . . . .	151
<b>9</b>	<b>Supplementary information</b>	<b>155</b>
	<b>Bibliography</b>	<b>181</b>
	<b>List of Figures</b>	<b>199</b>
	<b>List of Tables</b>	<b>213</b>
	<b>List of Symbols</b>	<b>215</b>
	<b>Acknowledgements</b>	<b>217</b>
	<b>Declaration</b>	<b>219</b>

Schlüsseltechnologien / Key Technologies  
Band / Volume 242  
ISBN 978-3-95806-562-8