

**DESIGN AND FABRICATION OF MAGNETIC
NANOWIRE ARRAY THIN FILMS
FOR HIGH-ENERGY PHOTON
PORTAL IMAGING**

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**Design and Fabrication of Magnetic Nanowire Array Thin Films for
High-energy Photon Portal Imaging**

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**A thesis submitted in fulfillment for the Degree of Doctor of Philosophy in Physics
in the Jomo Kenyatta University of Agriculture and Technology.**

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

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DEDICATION

This work is dedicated to: my loving wife Everlyne, daughters Yvonne, Priscilla and Sharon, and sons Vincent and Jesse, for their relentless provision of emotional support, understanding and encouragement; my hardworking mother Clemensia for her encouragement and patience; and my late father Alfonse.

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TABLE OF CONTENTS

DECLARATION.....	ii
DEDICATION.....	iii
ACKNOWLEDGEMENTS.....	iv
TABLE OF CONTENTS.....	vii
LIST OF TABLES.....	xiii
LIST OF FIGURES.....	xiv
LIST OF PLATES.....	xvii
LIST OF APPENDICES.....	xx
LIST OF ABBREVIATIONS.....	xxi
LIST OF SYMBOLS.....	xxiii
ABSTRACT.....	xxviii
CHAPTER 1	
LITERATURE REVIEW.....	1
1.0 Introduction.....	1
1.1 Spin-dependent tunneling in magnetic tunnel junctions (MTJs).....	2
1.2 Giant magnetoresistance (GMR) in magnetic nanowires.....	3
1.3 Current-induced magnetization in magnetic multiwires.....	5
1.4 Application of magnetic nanowires.....	6
1.4.0 Perpendicular magnetic recording.....	6
1.4.1 Photocurrent generation.....	7
1.4.2 Biological applications.....	8

1.5	Application of magnetic nanowire array for portal imaging.....	8
1.6	Fabrication of nanowires.....	12
1.7	Nanoporous anodic aluminium oxide (AAO) membranes.....	12
1.8	Magnetic nanowire synthesis by electrodeposition.....	14
1.9	Statement of the problem.....	15
1.10	Research objectives.....	15
1.11	Justification of the study.....	16
1.12	Outline of the thesis.....	17
 CHAPTER 2		
THEORY ON SOME PROPERTIES AND CHARACTERISTICS		
OF MAGNETIC NANOWIRE ARRAYS.....		
2.0	Magnetic nanowire array.....	18
2.1	Magnetism of nanowires.....	20
2.2	Magnetic materials.....	21
2.3	Magnetization process of a ferromagnetic/ferrimagnetic material.....	23
2.4	Magnetic structures.....	25
	2.4.0 Magnetic tunnel junctions (MTJs).....	25
	2.4.1 Origin of spin-dependent tunneling.....	29
	2.4.2 Metallic magnetic multilayers.....	30
2.5	Principal geometries of GMR measurement.....	32
2.6	Phenomenological theory of giant magnetoresistance (GMR).....	34
	2.6.0 Spin-dependent scattering.....	34

2.6.1	Spin-flip scattering.....	35
2.7	Fabrication of nanoporous AAO membranes.....	36
2.7.0	Anodizing process.....	36
2.7.1	Structure of the nanoporous AAO membranes.....	37
2.7.2	Growth of nanoporous AAO membranes.....	38
2.7.3	Theory of evolution of the nanoporous AAO structure.....	41
2.8	Cathodic electrolytic deposition (electrodeposition) process.....	45
2.8.0	Electrode process during electrodeposition.....	46
2.8.1	Mechanisms of the electrodeposition process.....	47
2.8.2	Structure and mode of growth of the electrodeposit.....	49
2.9	Electrochemical processes for anodizing and electrodeposition	51
2.9.0	Electrochemical cells and electrode processes.....	51
2.9.1	Ionic solutions (electrolytes) and electrical conduction.....	53
2.9.2	Activities of electroactive species	55
2.9.3	Ionic strength of electrolyte solutions.....	56
2.9.4	Electrochemical activity.....	59
2.9.5	Electrode potential.....	60
2.9.6	Types of electrode reactions.....	62
2.9.7	Electron transfer process at an electrode.....	63
2.9.8	Reaction rates.....	67
2.10	Transport of electroactive species	68
2.10.0	Migration component in the total current.....	70

2.10.1	Diffusion component in the total current	70
2.11	Potentiostatic of anodizing and electrodeposition processes.....	72
CHAPTER 3		
MATERIALS AND METHODS.....79		
3.0	Introduction.....	79
3.1	Materials and devices.....	80
3.2	Fabrication of the Faraday cage.....	83
3.3	Fabrication of the potentostat circuit.....	85
3.4	Fabrication of the electrochemical cells.....	88
3.4.0	Fabrication of the electrochemical cell fixture	91
3.4.1	Fabrication of the working electrode fixture.....	94
3.4.2	Fabrication of the sealing components.....	96
3.4.3	Reference electrode.....	97
3.4.4	Fabrication of the counter electrode.....	98
3.4.5	Fabrication of the cooler.....	99
3.4.6	Fabrication of the cooling jacket.....	101
3.4.7	Fabrication of the electropolishing fixture.....	103
3.5	Preparation of chemicals.....	104
3.6	Sample preparation and cleaning.....	104
3.7	Electropolishing of the substrates.....	107
3.8	Process of anodizing the substrates.....	109
3.9	Electrodeposition of nanowires in the pores of AAO membranes.....	114

3.10	Surface morphology of nanoporous AAO membranes.....	115
3.11	Influence of temperature and voltage on nanopore evolution.....	116
3.12	Scanning electron microscopy (SEM).....	116
	3.12.0 Sputtering of gold on the samples prior to SEM examination.....	116
	3.12.1 SEM examination of the samples.....	119
 CHAPTER 4		
RESULTS AND DISCUSSION.....		120
4.0	Introduction.....	120
4.1	Morphology of nanoporous anodic aluminium oxide (AAO).....	120
	4.1.0 Photograph of anodized aluminium substrate.....	120
	4.1.1 Influence of anodizing voltage on the surface morphology of nanoporous AAO membranes.....	123
	4.1.2 Influence of stirring by recirculation of electrolyte on the surface morphology of nanoporous AAO membranes.....	125
	4.1.3 Influence of anodizing temperature on the surface morphology of nanoporous AAO membranes.....	128
	4.1.4 Influence of cleaning, pretreatment and post-treatment chemicals on the surface morphology of nanoporous AAO membranes.....	131
	4.1.5 SEM micrographs of nanoporous AAO membranes.....	133
4.2.	Anodizing graphs.....	138
4.3	Electrodeposition of Ni-Fe nanowires in AAO templates.....	150
	4.3.0 SEM micrographs of Fe-Ni filled AAO membranes.....	150

4.3.1 Graphs for cathodic electrodeposition of Fe-Ni nanowires..... 151

CHAPTER 5

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK..... 153

5.0 Conclusions..... 153

5.1 Suggestion for further work..... 156

REFERENCES..... 157

APPENDICES..... 169

LIST OF TABLES

Table 3.0:	Conditions of anodizing different samples.....	114
Table 4.0:	Time trend analysis of the graph shown in Figure 4.5.....	147

LIST OF FIGURES

Figure 1.0:	High-energy photon imaging schematic diagram.....	9
Figure 1.1:	Magnetic nanowire imaging device.....	11
Figure 2.0:	Magnetic nanowires.....	19
Figure 2.1:	Magnetic multiwire array thin film.....	20
Figure 2.2:	Hysteresis loop of a ferromagnetic/ferrimagnetic material.....	24
Figure 2.3:	Magnetic tunnel junction.....	26
Figure 2.4:	Ferromagnetic and antiferromagnetic configurations of a metallic multilayer.....	31
Figure 2.5:	Geometries of giant magnetoresistance (GMR)	32
Figure 2.6:	Idealized structure of nanoporous AAO membrane.....	37
Figure 2.7:	Ion transport through oxide film during anodizing.....	39
Figure 2.8:	Evolution of pores in the nanoporous AAO membrane.....	42
Figure 2.9:	Evolution of current during the anodizing process.....	44
Figure 2.10:	Variation of electrodeposit structure with applied voltage.....	50
Figure 2.11:	Two-electrode cell for anodizing/electrodeposition.....	52
Figure 2.12:	Electron transfer at an inert metal electrode.....	64
Figure 2.13:	Energy distribution on the surface of a metal conductor.....	66
Figure 2.14:	Three-electrode cell for anodizing/electrodeposition.....	74
Figure 2.15:	Electrochemical cell as an impedance network.....	75
Figure 2.16:	A potentiostat circuit based on an operational amplifier.....	77

Figure 3.0:	Schematic diagram of the in-house built potentiostat circuit.....	86
Figure 3.1:	Schematic diagram of the cell fixture.....	92
Figure 3.2:	Schematic representation of the electrode fixture.....	94
Figure 3.3:	Schematic diagram of the electrolyte cooler.....	99
Figure 3.4:	Diagram showing how samples are mounted on the ion-sputter.....	117
Figure 4.0:	Effect of electrolyte replenishment on the surface of nanoporous AAO membranes.....	127
Figure 4.1:	Variation of voltage and current versus anodizing time for first anodizing step of sample RM002 at 25.4 ± 0.1 V dc and 4.0 ± 0.1 °C.....	139
Figure 4.2:	Variation of voltage and current versus anodizing time for first anodizing step of sample RM003 at 21.9 ± 0.1 V dc and 4.0 ± 0.1 °C.....	140
Figure 4.3:	Variation of voltage and current versus anodizing time for second anodizing step of sample RM002 at 25.4 ± 0.1 V dc and 4.0 ± 0.1 °C.....	141
Figure 4.4:	Comparison of evolution currents for first and second anodizing steps of sample RM002.....	143
Figure 4.5:	Effect of anodizing voltage on evolution current.....	146

Figure 4.6:	Effect of anodizing temperature on evolution current.....	149
Figure 4.7:	Comparison of the variation of voltage and evolution current versus electrodeposition time.....	152

LIST OF PLATES

Plate 3.0:	Photograph of the 2mx2mx2m Faraday cage.....	84
Plate 3.1:	Photograph of the in-house built potentiostat.....	87
Plate 3.2:	Photographs of the electrochemical cells.....	89
Plate 3.3:	Photograph of the electrodeposition cell fixture.....	90
Plate 3.4:	Photograph of the cell fixture.....	93
Plate 3.5:	Photograph of the electrode fixture.....	95
Plate 3.6:	Photograph of sealing components.....	96
Plate 3.7:	Photograph of the Ag/Ag/Cl reference electrode.....	97
Plate 3.8:	Photograph of the graphite counter electrode.....	98
Plate 3.9:	Photograph of the electrolyte cooler.....	100
Plate 3.10:	Photograph of the cooling jacket.....	101
Plate 3.11:	Photograph of the electrochemical cell and jacket assembly.....	102
Plate 3.12:	Photograph of the electropolishing cell fixture.....	103
Plate 3.13:	Photograph of partially desmuted samples.....	105
Plate 3.14:	Enlarged photograph of desmuted samples.....	106
Plate 3.15:	Photograph of the set-up for electropolishing samples.....	107
Plate 3.16:	Photograph of electropolished substrates in cuvettes.....	108
Plate 3.17:	Photograph of the experimental set-up for anodizing.....	110
Plate 3.18:	Photograph of refrigerated chiller.....	111
Plate 3.19:	Photograph showing frozen electrolyte on sample fixture.....	112

Plate 3.20:	Photograph of a “Dynamix” low-pressure pump.....	113
Plate 3.21:	Photograph of gold-sputtered samples.....	118
Plate 4.0:	Photograph of an aluminium substrate anodized at 15.0 V dc, 0 °C, and replenishment tube jet placed 20 mm from the surface of the sample.....	121
Plate 4.1:	Photograph of a magnified image of the membrane shown in Plate 4.0.....	122
Plate 4.2:	Photograph of an aluminium substrate anodized at 27.0 V dc, 0 °C, and replenishment tube jet placed 20 mm from the surface of the sample.....	124
Plate 4.3:	Photograph of an aluminium substrate anodized at 27.0 V dc, 0 °C, and replenishment tube jet placed 10 mm from the surface of the sample.....	125
Plate 4.4:	Photograph of an aluminium substrate anodized at 27.0 V dc, 0 °C, and replenishment tube jet placed 3 mm from the surface of the sample.....	126
Plate 4.5:	Photograph of an aluminium substrate anodized at 15.0 V dc, 22 °C, and replenishment tube jet placed 20 mm from the	

	surface of the sample.....	129
Plate 4.6:	Magnified view of the nanoporous AAO membrane in Plate 4.5.....	130
Plate 4.7:	Photograph of an aluminium substrate anodized at 15.0 V dc, 0 °C, and replenishment tube jet placed 10 mm from the surface of the sample.....	132
Plate 4.8:	Top view SEM image of a nanoporous AAO membrane obtained by anodizing aluminium at 15 V dc and 0 °C, for 10 minutes.....	133
Plate 4.9:	Top view SEM images of a nanoporous AAO membrane obtained by anodizing aluminium at 15 V dc and 0 °C, for 30 minutes.....	134
Plate 4.10:	Top view SEM image of a nanoporous AAO membrane obtained by nodizing aluminium at 15 V dc and 0 °C, for 3 hours.....	135
Plate 4.11:	Top view SEM image of a nanoporous AAO membrane obtained by anodizing aluminium at 15 V dc and 0 °C, for 3 hours, followed by second step anodizing for 1 hour.....	136
Plate 4.12:	Top view SEM image of a nanoporous AAO membrane obtained by anodizing aluminium at 25 V dc and 0 °C, for 3 hours, followed by second step anodizing for 1 hour.....	137
Plate 4.13:	Top view SEM image of Ni-Fe filled nanoporous AAO membrane....	150

LIST OF APPENDICES

Appendix A: Listing for first-step anodizing of sample RM002.....	171
Appendix B: Listing for first-step anodizing of sample RM003.....	180
Appendix C: Listing for second-step anodizing of sample RM002.....	192
Appendix D: Listing for electrodeposition of Fe-Ni nanowires.....	199

LIST OF ABBREVIATIONS

AAO	Anodic aluminium oxide
AC	Alternating current
AF	Antiferromagnetism
Ag/AgCl	Silver/silver chloride
BNC	British naval connector or Bayonet Neill-Cancelman
cc	Cubic centimetres
CE	Counter electrode
CIP	Current-in-plane
CPP	Current perpendicular-to-plane
dc	Direct current
e.m.f	Electromotive force
eV	Electronvolt
FM	Ferromagnetic/ferrimagnetic
GMR	Giant magnetoresistance
JMR	Junction magnetoresistance
K	Kelvin
MS/s	Million samples per second
MR	Magnetoresistance
MTJ	Magnetic tunnel junction

mV	Millivolts
NHE	Normal hydrogen electrode
nm	Nanometre
NM	Non-magnetic
OPA	Operational amplifier
pH	Pondus hydrogeni (hydrogen content)
PTFE	Polytetrafluoroethene
RE	Reference electrode
S/s	Samples per second
SEM	Scanning electron microscope
SHE	Standard hydrogen electrode
SPT	Spin polarized tunneling
SQUID	Superconducting quantum inference device
TMR	Tunnel magnetoresistance
V_{cc}	Voltage collector
v/v	Volume/volume
WE	Working electrode
μm	Micrometer

LIST OF SYMBOLS

ΔE	Closed-circuit cell potential difference
ΔE_n	Open-circuit cell potential difference
A	Surface or cross-sectional area
$a_{\square j}$	Electrochemical activity of species j
a_j	Chemical activity of species j
a_O, a_R	Activity of the oxidized species and reduced species
C	Concentration of electrolyte
c_{∞}	Concentration of electrolyte far from the electrode surface
c_j	Concentration of species j
c°	Standard concentration
c_O^b	Concentration of bulk solution
c_O, c_R	Concentration of oxidized species and reduced species
c_O^s, c_R^s	Electrode surface concentration of oxidized and reduced species
$D^{\uparrow}(E_F)$	Density of states of spin-up electrons at Fermi level
$D^{\downarrow}(E_F)$	Density of states of spin-down electrons at Fermi level
D_j	Diffusion coefficient of species j
D_o	Diffusion coefficient of oxidized species
E	Potential of electrode relative to reference electrode
E	Electron/electronic charge

E_a	Applied potential
E_F	Fermi level
E_n	Open-circuit electrode potential
E°_{WE}	Standard electrode potential of the working electrode
E_{redox}	Potential of the oxidized and reduced species couple
F	Faraday's constant
G	Total Gibbs energy
G	Gyromagnetic ratio
h	Planck's constant
I	Electric current
$i_d(t)$	Diffusion-limited current
i_j	Current of species j
i_m	Migration current due to all species
$i_{m,j}$	Migration current component due to species j
I_s	Spontaneous magnetization
J	Electric current density
J	Flux density
j_a	Anodic current density
j_c	Cathodic current density
$j_{d,j}$	Diffusion current density due to species j
j_j	Electric current density due to species j

J_j	Flux of species j
k_a	Oxidative reaction constant
k_B	Boltzmann constant
k_c	Reductive reaction constant
k^o	Standard rate constant
k^o	Formal rate constant
L	Distance between two points in solution
L	Angular momentum
M	Magnetic moment
M_L	Angular magnetic moment
M_S	Spin magnetic moment
m_e	Electronic mass
M_o	Molar mass
m_p	Proton mass
N	Number of nuclei on electrode surface during electrodeposition
N_A	Avogadro number
N_s	Number of nuclear sites
n	Number of electrons transferred per molecule
O_s	Oxidized species
P	Polarization
q	Electric charge

q_j	Charge of species j
r	Radius
R	Electric resistance
$R_{\uparrow\uparrow}$	Resistance when neighbouring magnetic layers are parallel
$R_{\uparrow\downarrow}$	Resistance when neighbouring magnetic layers are anti-parallel
R_0	Universal gas constant
R_s	Reduced species
s	Seconds
t	Time
V	Volt/voltage
V_{cc}^+	Positive power supply for operational amplifier
V_{cc}^-	Negative power supply for operational amplifier
v	Velocity
$v(\mathbf{x})$	Velocity of volume element along x direction
v_j	Velocity of species j
w	Work
w_j	Work done on species j
x	Distance from electrode surface along x-axis
z	Atomic/charge number
z_j	Atomic/charge number of species j
α	Electron transfer coefficient

γ_i	Activity coefficient
ϵ	Electrical permittivity
η	Electrode overvoltage or overpotential
κ	Nucleation constant
λ	Probability of electron tunneling
θ	Absolute temperature
μ_j	Electric mobility of species j
μ_0	Permeability of free space
ν_O, ν_R	Stoichiometric coefficients of oxidize and reduced species
ρ	Volumetric charge density
σ	Junction conductance
τ	Ionic strength
Φ	Electrostatic potential
$\Phi(x)$	Electrostatic potential at distance x from electrode surface
Φ^I, Φ^{II}	Electrostatic potential at region I and region II
Φ^0	Standard electrostatic potential
Λ	Conductivity of electrolyte

ABSTRACT

Ni-Fe magnetic nanowire array thin films that may be used to realize a magnetic portal imaging device were electrodeposited in the pores of anodic aluminium oxide (AAO) membranes. The membranes were first fabricated by a two-step process by anodizing 0.47 mm thick commercial aluminium foil in 0.50M sulphuric acid under constant dc potentials between 11V and 29V. The evolution current during the anodizing and electrodeposition processes were recorded using a data logger. The surfaces of the AAO films were studied at different stages of evolution of the nanopores and after electrodeposition of the Fe-Ni nanowires, using optical and electron microscopy. Results indicate that a barrier aluminium oxide thin film first formed on the aluminium surface prior to the formation of AAO membranes. The time for the formation of the barrier oxide decreased with increasing anodizing voltage, but was less than 40 seconds for AAO films synthesized at 15 V dc. It was also observed that 0.5 M sulphuric acid produced an organized nanopore pattern only after the second step anodizing process. It was noted that the amount of grey colour and pore diameter of AAO films increased with anodizing voltage, and low anodizing voltage and high temperature produced more surface defects. Current curves indicated that anodizing current, and hence rate of pore formation, decreased with temperature but increased with voltage. It was observed that electrodeposition of nanowires in AAO membranes took place in three stages, corresponding to deposition at the pore bottom, pore length and deposition outside the pores. In our study, the first nanopore was filled in approximately 710 s.