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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DECLARATION

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

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This thesis has been submitted for examination with our approval as University Supervisors.

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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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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
Vcc	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_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^o	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

$\mathbf{E_a}$	Applied potential
$\mathbf{E_F}$	Fermi level
$\mathbf{E_n}$	Open-circuit electrode potential
$\mathbf{E^o_{WE}}$	Standard electrode potential of the working electrode
$\mathbf{E_{redox}}$	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
$\mathbf{i_d(t)}$	Diffusion-limited current
$\mathbf{i_j}$	Current of species j
$\mathbf{i_m}$	Migration current due to all species
$\mathbf{i_{m,j}}$	Migration current component due to species j
$\mathbf{I_s}$	Spontaneous magnetization
J	Electric current density
J	Flux density
$\mathbf{j_a}$	Anodic current density
$\mathbf{j_c}$	Cathodic current density
$\mathbf{j_{d,j}}$	Diffusion current density due to species j
$\mathbf{j_j}$	Electric current density due to species j

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

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