THE EFFECT OF COMPOSITION, ANNEALING TEMPERATURE AND THICKNESS ON MAGNETORESISTANCE OF FERROMAGNETIC MULTILAYER STRUCTURES

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Specially dedicated to my beloved husband, Norazam Ahmad, and to my daughters, Nuraishah Maisarah and Nurul Hidayah.

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ABSTRACT

Giant Magnetoresistance (GMR) refers to a phenomenon of a considerable drop in electrical resistance in ultrathin ferromagnetic/non-magnetic layers structure, when a sufficiently high magnetic field is applied to the structure. Since the first time it was observed in late 1980's, this area of research has attracted a very strong interest due to the deep fundamental physics and its promising technological potential especially in data storage industry. This dissertation discusses the magnetoresistance of ferromagnetic/non-magnetic multilayers fabricated using electron beam evaporation technique. The magnetoresistance value is studied towards the effect of compositional variance, a range of post deposited annealing temperature, and multilayer thickness in terms of number of repetition of the bilayer as well as the non-magnetic layer thicknesses. The results on compositional variance show as deposited Co/Cu/Ni gives the largest magnetoresistance value of 8.75% followed by Ni/Cu/Ni (5.85%), Co/Ag/Co (2.64%) and Ni/Ag/Ni (1.48%). These four ferromagnetic multilayers were given heat treatment with a range of elevating temperature. The temperature ranges between 200°C to 350°C, resulting the magnetoresistance of the above structures increases to 14.25%, 10.68%, 7.45% and 4.38% respectively. However, the thermal stability for each multilayer systems were degraded after further annealing at a temperature called the blocking temperature. From the investigation, it was found that the blocking temperatures (or the optimum annealing temperature) for Co/Cu/Ni, Ni/Cu/Ni, Co/Ag/Co and Ni/Ag/Ni were 280°C, 290°C, 310°C and 280°C respectively. The study of thickness dependence GMR, focus only on Co/Cu/Co structures. It was shown that in $[Co/Cu/Co]_n$ structures, the magnetoresistance increase as n increases from 1 to 20. Meanwhile, for $Co_x/Cu_y/Co_x$ structures, the magnetoresistance increases as y decreases from 15 nm to 1 nm with x is fixed at 6 nm. The X-ray diffraction study for the optimum structures shows peaks of Co, Cu, Ni and Ag which describe the multilayers are in the crystalline form. The atomic force microscopy (AFM) image analysis for Co and Cu thin films with elevated annealing temperature reveals that the higher the annealing temperature, the larger the grain size of the multilayer. The EDX spectrum analysis confirmed the presence of Co, Cu, Ni, and Ag in the multilayers.

ABSTRAK

Kemagnetorintangan raksaksa (GMR) merujuk kepada satu penyusutan rintangan ketara dalam lapisan ferromagnet/bukan magnet ultra nipis apabila medan magnet yang cukup kuat dikenakan terhadap struktur tersebut. Semenjak pertama kali ditemui pada tahun 1988, bidang penyelidikan ini telah menarik minat yang kuat di kalangan penyelidik disebabkan oleh asas fiziknya yang mendalam dan potensi teknologinya terutama terhadap industri penyimpanan data. Tesis ini membincangkan magnetorintangan dari lapisan ferromagnet/bukan magnet yang di fabrikasi menggunakan kaedah penyejatan alur elektron. Nilai magnetorintangan dikaji terhadap tiga parameter utama iaitu kesan terhadap komposisi berlainan, kesan terhadap suhu sepuh-lindap selepas pendepositan, dan kesan ketebalan multilapisan tersebut dalam bentuk bilangan ulangan dwilapisan dan ketebalan lapisan bukan magnet. Keputusan dalam kajian variasi komposisi menunjukkan selepas pendepositan multilapisan Co/Cu/Ni memberikan nilai magnetorintangan tertinggi iaitu 8.75%, diikuti oleh Ni/Cu/Ni (5.85%), Co/Ag/Co (2.64%) dan Ni/Ag/Ni (1.48%). Keempat-empat struktur multilapisan ini kemudian diberikan rawatan suhu. Julat suhu adalah dari 250°C hingga 350°C. Hasilnya menunjukkan magnetorintangan struktur di atas masing-masing meningkat kepada 14.25%, 10.68%, 7.45% dan 4.38%. Walau bagaimanapun, kestabilan terma untuk setiap struktur multilapisan menurun pada suhu sepuh lindap yang lebih tinggi. Suhu ini dipanggil suhu sekatan. Daripada kajian, didapati suhu sekatan (ataupun suhu sepuh lindap optimum) untuk struktur Co/Cu/Ni, Ni/Cu/Ni, Co/Ag/Co dan Ni/Ag/Ni masing-masing adalah 280°C, 290°C, 310°C dan 280°C. Kajian tentang kesan ketebalan terhadap GMR difokuskan kepada struktur Co/Cu/Co sahaja. Pada struktur $[Co/Cu/Co]_n$, didapati magnetorintangan bertambah dengan meningkatya nilai n dari 1 hingga 20. Bagi struktur $Co_xCu_yCo_x$ pula, magnetorintangan bertambah apabila y menyusut dari 15 nm kepada 1 nm. Kajian belauan sinar-X terhadap terhadap struktur multilapisan optimum menunjukkan kehadiran puncak-puncak Co, Cu, Ni dan Ag, yang mana menunjukkan multilapisan berstruktur hablur. Analisis imej mikroskop imbasan daya atom terhadap filem nipis Co dan Cu bagi suhu yang meningkat menunjukkan pada suhu sepuh lindap yang lebih tinggi, saiz butiran multilapisan adalah lebih besar. Analisis spektrum serakan tenaga sinar-X mengesahkan kehadiran unsur-unsur Co, Cu, Ni dan Ag dalam multilapisan yang dikaji.

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LIST OF ABBREVIATIONS

OMR	-	Ordinary magnetoresistance
AMR	-	Anisotropic magnetoresistance
GMR	-	Giant magnetoresistance
CMR	-	Colossal magnetoresistance
TMR	-	Tunnelling magnetoresistance
AFM	-	Atomic force microscope
FESEM	-	Field emission scanning electron microscope
XRD	-	X-Ray diffractometer
EDX	-	Energy dispersive X-Ray
HDD	-	Hard disk drive
CIP	-	Current-in-plane
MBE	-	Molecular beam epitaxy
DC	-	Direct current
RF	-	Radio Frequency
MRAM	-	Magnetic random access memory
MTJ	-	Magnetic tunnel junction
FTM	-	Film thickness monitor
DFT	-	Density functional theory
FM	-	Ferromagnetic
NM	-	Non-magnetic
RMS	-	Root mean square

LIST OF SYMBOLS

Ag	-	Argentum
B	-	Magnetic flux density
C	-	Quartz constant
Co	-	Cobalt
Cu	-	Copper
d_{NM}	-	Non-magnetic layer thickness
d_{FM}	-	Ferromagnetic layer thickness
d	-	Thickness, film
d	-	Plane spacing in atomic lattice
E	-	Electric field
e	-	Charge of electron
F	-	Correction factor
f	-	Frequency
Δf	-	Frequency change
H	-	External magnetic field
H_s	-	Saturation magnetic field
I	-	Current
$i_{\uparrow,\downarrow}$	-	Intrinsic resistivities for spin channels
J_n	-	Exchange constant
K	-	Breadth constant
k_F	-	Fermi's momentum

L	-	Crystallite length
l_{NM}	-	Mean free path of conduction electron
MR	-	Magnetoresistance
MR%	-	Magnetoresistance ratio
m	-	Mass of electron
Ni	-	Nickel
n	-	Avogadro number
n	-	Integer, determine by order
$n\ (E_f)$	-	Density of states
N	-	Number of four layer unit cells withimultilayermultilayer multilayer
R	-	Resistance
R	-	Resistance, at certain magnetic field
R_{AP}	-	Resistance for anti-parallel alignment
R_P	-	Resistance for parallel alignment
R_{min}	-	Saturation magnetoresistance
$R_{\uparrow,\downarrow}$	-	Resistance for two spin channel
R_s	-	Semiconductor sheet resistance
Si	-	Silicon
$Si_3\ N_4$	-	Silicon nitride
T	-	Temperature
T_c	-	Curie temperature
V	-	Voltage
Z_i	-	Height value of each point
Z_{ave}	-	Average surface height
α	-	Spin asymmetry parameter
β	-	Breadth of peak phase
σ	-	Independent conductivity
$\sigma_{\uparrow}$	-	Conductivities for up-spin
$\sigma_{\downarrow}$	-	Conductivities for down-spin
σ_{Drude}	-	Drude’s conductivity

$\rho_{\uparrow}$	-	Spin-up
$\rho_{\downarrow}$	-	Spin-down
ρ_{NM}	-	Resistivity of non-magnetic layer
ρ_q	-	Quartz density
ρ_f	-	Thin film density
υ_F	-	Fermi's velocity
$\overline{\upsilon}$	-	Velocity in spin channel
λ	-	X-ray wavelength
λ	-	Mean free path
π	-	Pai
τ	-	Relaxation time of electrons
$\hbar$	-	Planck constsnt
μ	-	Micro
θ	-	Angle
δ_{RMS}	-	Root mean square roughness
2θ	-	Diffraction angle (two-theta)
Δ	-	Delta
θ	-	Angle
$<$	-	Less than

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CHAPTER 1

INTRODUCTION

1.1 Background of Research

The phenomenon of magnetism, that is the mutual attraction of two pieces iron or iron ore had been known since 4000 years ago. The ancient Greeks have been reported to experiment with this mysterious force but the application were limited at that time, until scientific research was made by William Gilbert (1504-1603) 400 years ago. He wrote the book 'De Magnet' which explained his research findings on magnetic properties. Before 19th century, the only important application of magnet is Compass.

Hans Christian Oersted (1775-1851) observed that magnetic field interact with electric current in 1820. Inspired with this, he creates the first electromagnet in 1825 based on the principle that electric current produce magnetic field. This was a scientific breakthrough in magnetism and since that, researches towards magnetic material were rapidly grown and its applications were widely increased.

Magnetoresistance is the properties of some materials to lose or gain electrical resistance when an external magnetic field is applied to them. The effect was first discovered by William Thomson in 1857, but he was unable to lower the electrical resistance by more than 5%. This effect was later called ordinary magnetoresistance (OMR). Ordinary magnetoresistance arises from the effect of Lorentz force on the electron trajectories due to the applied magnetic field. It does not saturate at the saturation magnetic field and usually small in metals which is less than 1% in fields of 1 Tesla (Tsymbal and Pettifor, 2001). More recent researches discovered materials showing anisotropic magnetoresistance (AMR), giant magnetoresistance (GMR), colossal magnetoresistance (CMR) and tunneling magnetoresistance (TMR).

The discovery of giant magnetoresistance phenomena in 1988 was a breakthrough in magnetic material and thin film magnetism. Since then, researches in thin film magnetism are looking forward to obtain larger magnetoresistance ratio because in principal, larger magnetoresistance ratio ascribe bigger data storage volume.

1.2 Introduction to Giant Magnetoresistance

Giant Magnetoresistance or GMR is a quantum mechanical effect observed in thin film structures composed of alternating ferromagnetic and non-magnetic layers. The effect is a significant decrease in electrical resistance in the presence of magnetic field. In the absence of an applied magnetic field, the direction of magnetization of adjacent ferromagnetic layers is antiparallel due to a weak anti-ferromagnetic coupling between layers, and it decreases to a lower level of resistance when the magnetization of the adjacent layers align due to an applied external field. The spins of the electrons of the non-magnetic metal align parallel or antiparallel with an applied magnetic field in equal numbers, and therefore suffer less magnetic scattering when the magnetizations of the ferromagnetic layers are parallel.

Figure 1.1 shows the schematic representation of GMR effect. The upper diagram (a), shows change in the resistance of the magnetic multilayer as a function of applied magnetic field. The middle diagram (b), is the magnetization configurations (indicated by the arrows) of the multilayer at various magnetic field. The diagram shows that the magnetizations are aligned antiparallel at zero field whereas the magnetizations are aligned parallel when the external field H is larger than the saturation field H_s. The lower diagram (c), shows the magnetization curve of the magnetic multilayer.

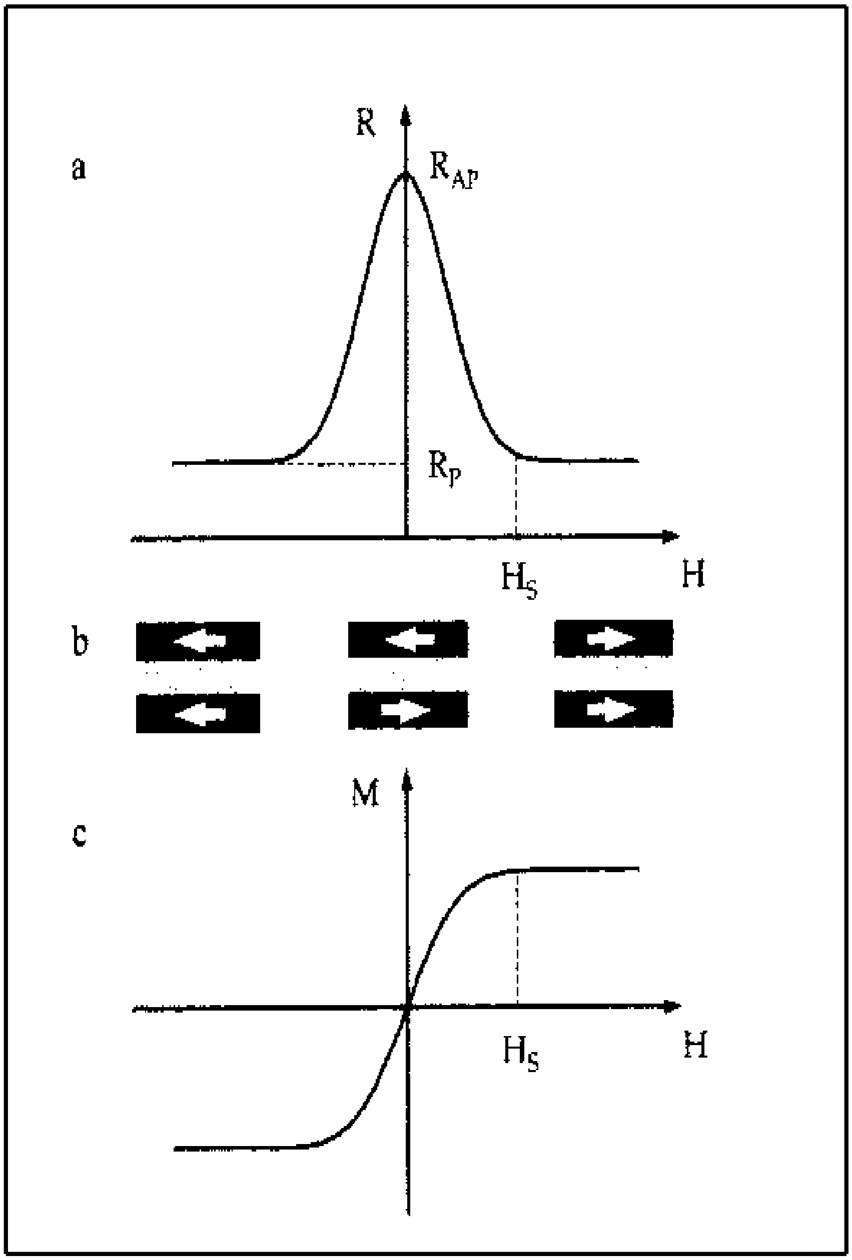

Figure 1.1: Schematic representation of the GMR effect, after Tsymbal and Pettifor, 2001.

1.3 Research Objectives

This dissertation was carried out to reach the following objectives:

i. To fabricate and design the GMR structures by electron beam evaporation method.

ii. To study the effect of fabrication parameters and post-annealing parameters towards the GMR values.

iii. To investigate the dependencies of composition, annealing temperature and thickness on the GMR value.

1.4 Research Scopes

This dissertation emphasizes on deposition and characterization of different ferromagnetic multilayer structures. A ferromagnetic multilayer structure basically consists of ferromagnetic layer separated by a thin conducting non-magnetic layer. Ferromagnetic materials used in this study are Cobalt (Co) and Nickel (Ni). The conducting materials used are Copper (Cu) and Argentum (Ag). The multilayer structures studied are namely Co/Cu/Ni, Ni/Ag/Ni, Co/Ag/Co and Ni/Cu/Ni. These ferromagnetic multilayer structures were deposited using electron beam method, which were then followed by annealing. The Magnetoresistance Ratio (MR%) for each structures is measured, focusing on effect of different fabrication and post-annealing parameters. The following parameters are studied: Composition difference of ferromagnetic materials and conducting materials; annealing temperature ranged from 200°C to 350°C; conducting layer thickness vary from 1 to 15 nm, and the number of the repetition of the bilayer from 1 to 20 bilayer. Structural characterizations using methods of Atomic Force Microscopy, Field Emission Scanning Electron Microscopy and X-Ray Diffractometry are also carried out as supportive evidences of the result obtained.

Atomic Force Microscope (AFM) was used to probe the surface morphology of the magnetic and non-magnetic thin film layer. Field Emission Scanning Electron Microscope (FESEM) was used to see the surface structure of the magnetic and non-magnetic thin film layer. X-Ray Diffractometer (XRD) was used to provide information about the crystallographic structure of the magnetic and non-magnetic layer.

1.5 Research Problem Statement

In the early 1980s, thin film magnetism was applied to higher-density to nonvolatile random access memory by Honeywell in their development of anisotropic magnetoresistance (AMR) memory. Later, a new path leading to the integration of magnetic devices into computer technology began to emerge with the discovery of giant magnetoresistance (GMR). GMR heads are more sensitive compared to the previous anisotropic magnetoresistive (AMR) heads.

Different from GMR heads, an AMR heads employs a special conductive material that changes its resistance in the presence of magnetic field. As the head passed over the surface of the disk, this material changes its resistance as the magnetic fields changes corresponding to the stored patterns on disk. A sensor is used to detect these changes in resistance, which allows the bits on platter to be read. While the older AMR heads typically exhibit about 2% of resistance change when passing from one magnetic polarity to another, for GMR heads the value is between 5% to 8%. This means GMR heads can detect much weaker and smaller signals, which is the key to increasing areal density.

Magnetic disk drive products have had their areal density increased by factor of 35 million since the introduction of the first disk drive, in 1957. Since 1991, the rate of increase has accelerated to 60% per year, and since 1997 it has accelerated further to an incredible 100% per year (Wolf et. al, 2006). The acceleration was the result of the introduction of AMR read heads in 1991 and GMR read heads in 1997. Today, nearly all disk drives in the industry incorporated the GMR read-head design, which is faster in speed and smaller in size. The achievements of switching from AMR read head technology to GMR read head technology would not be possible without a detailed understanding of the physics of GMR.

To further understand GMR, a deeper insight into ferromagnetic multilayer structures is pertinent. The technique of fabrication, fabrication parameters such as material composition, number of bilayer, non-magnetic layer thickness and also the post annealing treatment, produces a variety of spin transport behavior in ferromagnetic multilayer structures. All these parameters significantly influence the GMR effect in the structures.

Study on magnetic and non-magnetic material composition can provide better understanding on magnetic and non-magnetic coupling in GMR phenomenon. Detailed information about band structure and lattice matching could be associated. From the study on post annealing treatment, the GMR response on a range of annealing temperatures could be observed. Study on the number of bilayer could enhance the understanding of spin dependent transport where supportive evident to resistor model could be obtained. The GMR response towards increasing non-magnetic layer thickness could be provided from the non-magnetic layer thickness study.

1.6 Thesis Outline

A general background and brief introduction to GMR effect are discussed in Chapter 1. This is followed by objectives, scope of the study, significances of the study and the outline of the dissertation. In Chapter 2, an overview of GMR properties in ferromagnetic multilayer structures is presented. Chapter 3 discussed about the methodology which is focused on fabrication procedures, measurement technique and characterization technique of ferromagnetic multilayers. A general overview of the measurement and characterization technique is discussed. Results of all the experimental work such as effects on the GMR towards composition difference, various annealing temperature, various conducting layer thickness, number of the repetition of the bilayer and also structural characterization are presented in Chapter 4. Chapter 5 summarizes and concludes the findings obtain in the earlier chapter, and also provides suggestions for future work in this area of research.