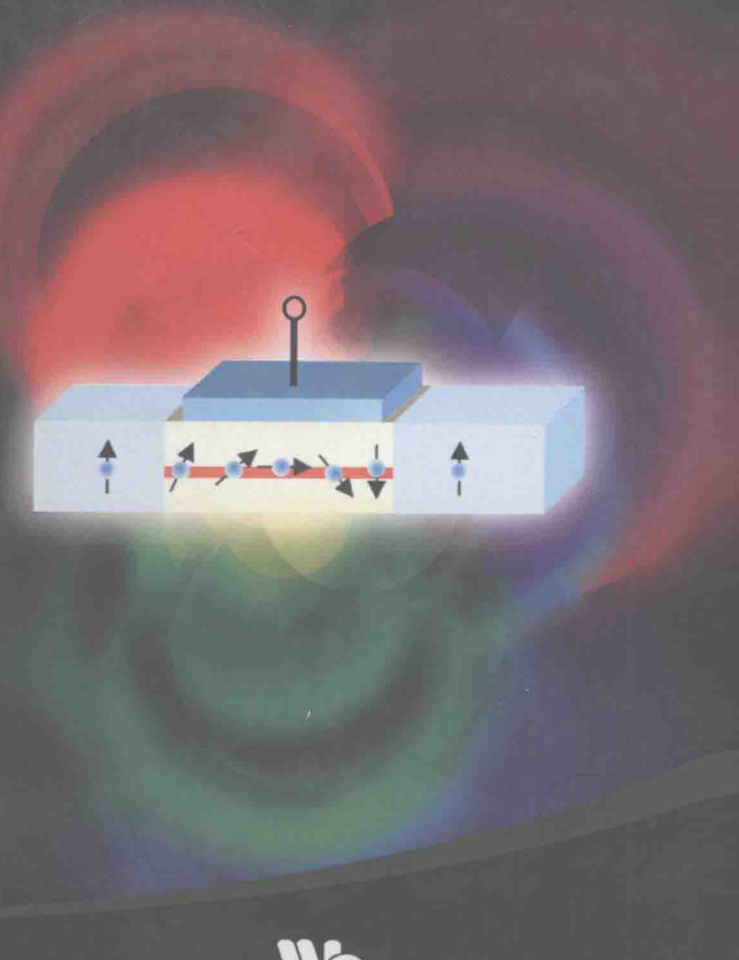
SEMICONDUCTOR SPINTRONICS

Jianbai Xia • Weikun Ge • Kai Chang



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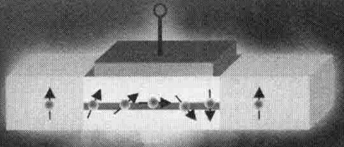

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SEMICONDUCTOR
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PREFACE

This book introduces the developing history of semiconductor spintronics, basic concepts, and research fruits and prospected future development. It includes Introduction and 10 chapters. The introduction introduces the developing history of semiconductor spintronics. Chapter 1 introduces the properties of magnetic ions in semiconductors, energy-level splitting of magnetic ions in the crystal field, and energy-level characteristics of the basic state and low excited states. Chapter 2 introduces the properties of dilute magnetic semiconductors, giant Zeeman splitting effect, and optical properties. Chapter 3 introduces ferromagnetic semiconductors, ferromagnetic interaction theory, and factors influencing the Curie temperature. Chapter 4 introduces the injection of spin electron, Rashba effect, coherent transport of spin through hetero-interface, experiments and theories of injection of spin-polarized electrons. Chapter 5 introduces spin relaxation, three main mechanisms of spin flip — EY, DP, and BAP mechanisms — and experimental studies of spin relaxation. Chapters 6–10 are special research topics, introducing some recent research fruits. Chapter 6 introduces the theoretical basis and experimental measurements of Rashba and Dresselhaus effects. Chapter 7 is on the optical responsibility of spin, including spin photocurrent induced by optically injected electron spin and electron spin polarization derived by the electric field, in spin-splitting systems. Chapter 8 is on the control of spin coherent electrons, including electron spin coherence, their spatial movement, spin Hall effect, production of spin current, and spin dynamics in semiconductors. Chapter 9 is about transport of spin-polarized electrons and magnetic domains, including the spin transport of two-dimensional electron gas and quantum dot of magnetic semiconductors, and magnetic domain transport in magnetic semiconductors. Chapter 10 deals with spin property control in semiconductor quantum dots and wires, including the control of g-factors and Rashba coefficient by changing the shape and size of dots and wires, N doping, and applied electric or magnetic fields. This book is suitable for high-level students in university, postgraduates, and professors and researchers.

LIST OF ACRONYMS

1D	one-dimensional
2D	two-dimensional
2DEG	two-dimensional electron gas
BIA	bulk inverse asymmetry
CB	conduction band
CFR	crystal-field resonance
CISP	current induced spin polarization
CP	circularly polarized
CPGE	circular photo-galvanic effect
DBH	dangling band hybrid
DMS	dilute magnetic semiconductor
DTS	differential transmission spectrum
DW	domain-wall
EMA	effective mass approximation
ESR	electron spin resonance
FET	field effect transistor
FFT	fast Fourier transform
FMS	ferromagnetic semiconductor
FT	Fourier transform
FR	Faraday rotation
FWHM	full-width at half-maximum
GMR	giant magnetic resistance
HRTEM	high resolution transmission electron microscopy
KR	Kerr rotation
LED	light emitting diode
LH	left hand
MBE	molecular beam epitaxy
MCD	magnetic circular dichroism
MOKE	magneto-optical Kerr effect
MP	magnetic polaron
MPGE	magneto-photogalvanic effect

MQW	multiple quantum well
MR	magnetoresistance
MRAM	magnetic random access memory
OS	oxidation state
PEM	photoelectric modulator
PL	photoluminescence
QD	quantum dot
QDQW	QD quantum well
QW	quantum well, quantum wire
QUIC	quantum interference control
RF	radio frequency
RH	right hand
RHEED	reflection high-energy electron diffraction
RSA	resonant spin amplification
RSHE	reversed spin Hall effect
RSS	Rashba spin splitting
RT	room temperature
SdH	Shubnikov-de Haas
SEM	scanned electron microscopy
SGE	spin-galvanic effect
SIA	structure inverse asymmetry
SL	square loop
SOC	spin-orbit coupling
SOI	spin-orbit interaction
SPC	spin polarized current
SQUID	superconducting quantum interference device
SRT	spin relaxation time
TE	transverse electric (field)
TEM	transmission electron microscopy
TM	transition metal
TM	transverse magnetic (field)
TMR	tunneling magnetoresistance
TRFR	time-resolved Fadaday rotation
VCSEL	vertical-cavity surface emitting laser
XRD	X-ray diffraction

CONTENTS

INTRODUCTION

Spintronics studies the use of spin freedom of electrons. It originated from the giant magnetic resistance (GMR) effect found by Fert and Gruenberg, respectively, in 1988. This discovery produced highly sensitive magnetic sensors, used in the read-out head of the magnetic hard disk. Just after 9 years as the GMR was discovered, in November 1997 IBM Co. declared that they fabricated the commercial read-out head of the magnetic hard disk. This product accomplished an enterprise of several billions of US dollars. The spin electronic devices under study include magnetic random access memory (MRAM), spin field effect transistor (FET), spin-polarized laser, etc. These devices depend on their ability to control spin in the solids and they can be used to decrease the power consumption, to overcome the velocity limit connected with the charge electrons, and in the quantum information treatment and quantum computation in future.

The study contents include: production, transport, tunneling of spin-polarized electrons, optical phenomena, lifetime, decoherence mechanism connected with them, etc. A semiconductor is the best material to study spintronics, because: (1) the number of carriers in a semiconductor is relatively few, and their behavior can be looked as that of a single particle, excluding the many-particle effect; (2) the qualities of semiconductor single crystals, heterostructures, quantum wells, or quantum dots (QDs) can be made to be very perfect, so that the lattice defects and impurities can be decreased to the least degree, and the relaxation of electron spins can be decreased; (3) semiconductors are "transparent" to most part of the light; thus, one can inject and detect spin electrons by circularly polarized (CP) light; (4) the semiconductor device technology is advanced, and it is easier to make devices, integrate devices, or integrate with other devices. But a semiconductor has a shortcoming: it is nonmagnetic. Its magnetism has to dope magnetic ions from outside; while the solubility of the magnetic ions in the semiconductor is smaller, the concentration of magnetic impurity in semiconductors is generally several percent higher. Therefore, the

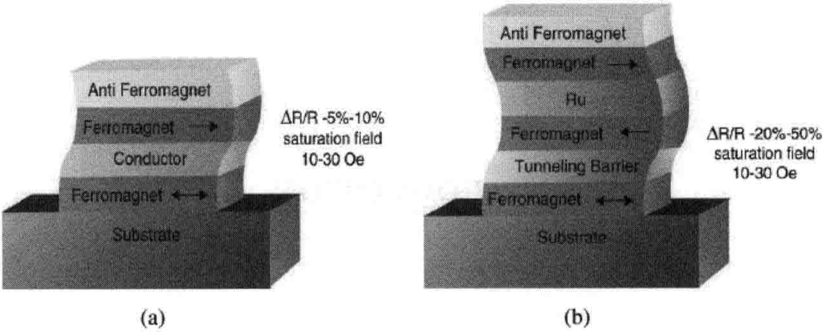

Fig. 0.1. Schematic diagram of (a) spin valve and (b) MTJ proposed on the basis of the GMR effect (Wolf *et al.*, 2001).

formation of the spin-polarized electron in the semiconductor is a difficult problem.

0.1. Origin of Spintronics — GMR Effect Device

In 1988, the GMR effect was discovered in a three-layer thin film structure, as shown in Fig. 0.1(a). In this structure, the above and underneath layers are ferromagnetic materials, for example, alloys of Fe, Co, and Ni, and the middle layer is a nonmagnetic material, for example, Cu. When the magnetic moments of above and underneath layers are parallel, the resistance of the material is smallest; when the magnetic moments are antiparallel, the resistance is largest. The current can be perpendicular to the interface (CPP) and also can be parallel to the interface (CIP). This effect exists at room temperature (RT). When a rather small magnetic field (~100 Oe) changes the orientation of one ferromagnetic layer, one can observe obvious variations in the resistivity (~10%).

On the basis of the GMR effect, the spin valve was proposed, as shown in Fig. 0.1(a). An antiferromagnetic layer is added on the above ferromagnetic layer. The antiferromagnetic layer makes the magnetic moment of the above ferromagnetic layer hardly to change the direction in the external magnetic field, i.e. it plays a "nail-up" role of the magnetic moment. The underneath ferromagnetic layer is free, and its magnetic moment direction can be changed in the external small magnetic field. When the magnetic moments of the above and underneath layers become antiparallel, the resistance generally increases 5–10%.

Magnetic tunnel junction (MTJ), as shown in Fig. 0.1(b), consists of above nail-up layer (two ferromagnetic layers, and a thin layer of Ru placed in between them, form a strong antiferromagnetic coupling), underneath free ferromagnetic layer, and middle thin insulator layer (generally Al_2O_3). The insulator layer acts as a potential barrier layer, and the tunneling current is perpendicular to the interface. When the moments of the above and underneath ferromagnetic layers change from parallel to antiparallel, the tunneling resistance changes 20–30%, similar to the spin valve, but the modulation range is large. Because the tunneling current density is generally small, the MTJ device has a high resistance.

The application of the spin valve and MTJ device is wide, for example, magnetic field sensors, read-out head of the magnetic disk, galvanic isolators, MRAM, etc. GMR spin valve read-out head is the main part of the magnetic disk driver; nearly all commercial GMR heads are the spin valve forms originally proposed by IBM. After improvement, for example, using the antiferromagnetic layer as the nail-up layer (as shown in Fig. 0.1(b)), the increase in the magnetic resistance rises from 5% to today's 20%. Now the memory density of the hard disk has approached 100 Gbits per square inch. The stripe width of the sensors approaches $0.1\,\mu m$, the current density becomes very large, and the demand for the sensitivity of the spin valve becomes more high and high.

MRAM uses the property of the magnetic hysteresis loop to store up data and uses the magnetic resistance to read out data. When the GMR-based MTJ and the memory unit of spin valve are integrated into an integrated circuit chip, its function is like a general semiconductor random access memory. But it has an advantage, the data can be retained with power off. Compared with the electrically erasable programmable read-only memory (EEPROM) and the flash memory, the write time of the MRAM is 1000 times faster; besides, there is no wearout in the write cycling and low power consumption for writing, while the EEPROM and flash memory will wear out after one million write circles. The MRAM data access times are about 1/10,000 that of hard disk drives. MRAM is not yet available commercially.

0.2. New Materials for Spintronics Applications

The search for material-combining properties of the ferromagnet and the semiconductor has been a long-standing and elusive goal, due to the large