LIST OF TABLES

4.1 Calculated values of various fields on MTJ . . . . . . . . . . . . . . . . . . . . . . . . . . . 63

5.1 Threshold switching currents of various fields and torques on MTJ . . . . . . . . . . . . 76
# LIST OF FIGURES

1.1 Growth of MR in storage industry .............................................. 2
1.2 Principle of writing data ....................................................... 3
1.3 Structure of a magnetic cell ................................................... 4
1.4 Reading data (a) CIP (b) CPP .................................................. 4
1.5 Magnetization (a) Parallel (b) Anti-parallel .............................. 5
1.6 (a) A nanomagnet (b) Principle of writing data ......................... 7
1.7 MRAM with external field for writing data ............................... 8
2.1 M-H curves ................................................................. 14
2.2 Magnetic ordering in different materials .................................. 15
2.3 Exchange coupling in transition metals .................................... 17
2.4 Hysteresis loop ............................................................ 18
2.5 Origin of magnetic moment .................................................. 20
2.6 Spin occupancy in 3d orbital ................................................ 21
2.7 Magnetic fields of lines (a) in a dipole (b) in a coil .................... 22
3.1 Energy levels and wave functions of a free electron in a line of length L 26
3.2 Energy versus wave vector of free electron ............................. 27
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3</td>
<td>DOS (a) without applied field and (b) with applied field.</td>
</tr>
<tr>
<td>3.4</td>
<td>Potential barrier (a) Rectangular (b) Irregular</td>
</tr>
<tr>
<td>3.5</td>
<td>Turning point</td>
</tr>
<tr>
<td>3.6</td>
<td>M/I/M structure with a trapezoidal barrier</td>
</tr>
<tr>
<td>3.7</td>
<td>Energy-band diagram of MTJ</td>
</tr>
<tr>
<td>3.8</td>
<td>Spin dependent tunneling when FM(_1) and FM(_2) are parallel.</td>
</tr>
<tr>
<td>3.9</td>
<td>Spin dependent tunneling when FM(_1) and FM(_2) are antiparallel.</td>
</tr>
<tr>
<td>3.10</td>
<td>Energy band diagram for a M/I/M with external bias</td>
</tr>
<tr>
<td>4.1</td>
<td>Demagnetization field of an ellipsoid</td>
</tr>
<tr>
<td>4.2</td>
<td>Demagnetization fields in standard structures</td>
</tr>
<tr>
<td>4.3</td>
<td>Circular disc placed in y – z plane</td>
</tr>
<tr>
<td>4.4</td>
<td>Dipolar field due to a magnetic dipole</td>
</tr>
<tr>
<td>4.5</td>
<td>Top view of FLs in an array</td>
</tr>
<tr>
<td>4.6</td>
<td>Coupling between two MTJs (i) and (j)</td>
</tr>
<tr>
<td>4.7</td>
<td>Array that requires the maximum and minimum switching currents</td>
</tr>
<tr>
<td>4.8</td>
<td>Magnetostatic field from PL to FL</td>
</tr>
<tr>
<td>4.9</td>
<td>Exchange field between PL and FL</td>
</tr>
<tr>
<td>4.10</td>
<td>Variation of exchange energy with barrier height</td>
</tr>
<tr>
<td>4.11</td>
<td>Variation of exchange constant with barrier thickness</td>
</tr>
<tr>
<td>4.12</td>
<td>Spin torque experienced by FL electrons</td>
</tr>
</tbody>
</table>
4.13 Variation of $\tau_s$ and $H_{ex}$ for varying barrier thickness ........................................ 58
4.14 Oersted field in a circular disc ................................................................. 59
4.15 FL with infinitesimal magnetizations on its surface .............................................. 60
4.16 Single domain approximation ........................................................................ 62
4.17 Pairs of micromagnetic elements approximated as a single dipole .................. 62

5.1 Trajectory of a magnetic moment ................................................................. 66
5.2 Directions of the precession and damping torques ........................................... 67
5.3 Directions of the precession, damping and spin torques .................................. 68
5.4 Equivalent circuit of a single nanomagnet ...................................................... 70
5.5 Precession of a magnetic moment ................................................................. 71
5.6 Trajectory of a magnetic moment switching from $+z$ to $-z$ .......................... 71
5.7 $M_x$, $M_y$ and $M_z$ of a magnetic moment .................................................... 71
5.8 Phase difference of $x$ and $y$ component of magnetic moment ........................ 72
5.9 Variation of the parameters $\phi$ and $\theta$ with variation in time ....................... 73
5.10 Variation of switching threshold $V_{app}$ for varying barrier thickness ............ 74
5.11 $V_{\text{thresh}}$ variations with barrier thickness for MgO and Al$_2$O$_3$ barriers .... 78
5.12 A basic non-volatile STT gate ................................................................. 79
5.13 Switching of a non-volatile STT logic gate .................................................... 80
5.14 A non-volatile 2:4 decoder circuit ............................................................... 81
5.15 Output of a 2:4 decoder for an input $AB=11$ ............................................. 82
## LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTJ</td>
<td>Magnetic tunnel junction</td>
</tr>
<tr>
<td>MRAM</td>
<td>Magnetic random access memory</td>
</tr>
<tr>
<td>STT</td>
<td>Spin transfer torque</td>
</tr>
<tr>
<td>STTRAM</td>
<td>STT random access memory</td>
</tr>
<tr>
<td>FL</td>
<td>Free layer</td>
</tr>
<tr>
<td>PL</td>
<td>Pinned layer</td>
</tr>
<tr>
<td>MR</td>
<td>Magnetoresistance</td>
</tr>
<tr>
<td>AMR</td>
<td>Anisotropic magnetoresistance</td>
</tr>
<tr>
<td>TMR</td>
<td>Tunneling magnetoresistance</td>
</tr>
<tr>
<td>GMR</td>
<td>Giant magnetoresistance</td>
</tr>
<tr>
<td>M</td>
<td>Metal</td>
</tr>
<tr>
<td>FM</td>
<td>Ferromagnet</td>
</tr>
<tr>
<td>NM</td>
<td>Non-magnetic metal</td>
</tr>
<tr>
<td>I</td>
<td>Insulator</td>
</tr>
<tr>
<td>CIP</td>
<td>Current in plane</td>
</tr>
<tr>
<td>CPP</td>
<td>Current perpendicular to plane</td>
</tr>
<tr>
<td>SWE</td>
<td>Schödinger’s wave equation</td>
</tr>
<tr>
<td>DOS</td>
<td>Density of states</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary metal oxide semiconductor</td>
</tr>
<tr>
<td>LLGE</td>
<td>Landau Lifshitz Gilbert equation</td>
</tr>
<tr>
<td>SPICE</td>
<td>Simulation program with integrated circuit emphasis</td>
</tr>
<tr>
<td>AFM</td>
<td>Antiferromagnet</td>
</tr>
<tr>
<td>BCC</td>
<td>Body centered cube</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>PS</td>
<td>Parallel state</td>
</tr>
<tr>
<td>APS</td>
<td>Antiparallel state</td>
</tr>
<tr>
<td>NV</td>
<td>Non-volatile</td>
</tr>
<tr>
<td>$S$ matrix</td>
<td>Scattering matrix</td>
</tr>
<tr>
<td>$T$ matrix</td>
<td>Transfer matrix</td>
</tr>
<tr>
<td>det</td>
<td>Determinant</td>
</tr>
<tr>
<td>USF</td>
<td>Unit step function</td>
</tr>
<tr>
<td>Notation</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>$R_P$</td>
<td>Resistance when FM$_1$ and FM$_2$ are parallel</td>
</tr>
<tr>
<td>$R_{AP}$</td>
<td>Resistance when FM$_1$ and FM$_2$ are antiparallel</td>
</tr>
<tr>
<td>$H_{app}$</td>
<td>Applied magnetic field</td>
</tr>
<tr>
<td>$\mu_0$</td>
<td>Permeability of free space</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Relative permeability</td>
</tr>
<tr>
<td>$e$</td>
<td>Charge of an electron</td>
</tr>
<tr>
<td>$m_e$</td>
<td>Mass of an electron</td>
</tr>
<tr>
<td>$h$</td>
<td>Planck’s constant</td>
</tr>
<tr>
<td>$\hbar$</td>
<td>Reduced Planck’s constant ($h/2\pi$)</td>
</tr>
<tr>
<td>$K$</td>
<td>Boltzmann’s constant</td>
</tr>
<tr>
<td>$\mu_B$</td>
<td>Bohr magneton</td>
</tr>
<tr>
<td>$m$</td>
<td>Magnetic moment</td>
</tr>
<tr>
<td>$\chi$</td>
<td>Susceptibility</td>
</tr>
<tr>
<td>$g$</td>
<td>Landé g-factor</td>
</tr>
<tr>
<td>$l$</td>
<td>Orbital quantum number</td>
</tr>
<tr>
<td>$m_l$</td>
<td>Orbital moment</td>
</tr>
<tr>
<td>$a$</td>
<td>Distance from the nucleus to the electron</td>
</tr>
<tr>
<td>$s$</td>
<td>Spin quantum number</td>
</tr>
<tr>
<td>$m_s$</td>
<td>Spin moment</td>
</tr>
<tr>
<td>$\mathcal{E}_F$</td>
<td>Fermi energy</td>
</tr>
<tr>
<td>$\mathcal{E}$</td>
<td>Energy of particle</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>Spin splitting energy</td>
</tr>
<tr>
<td>$\mathcal{H}$</td>
<td>Hamiltonian</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>Decay constant</td>
</tr>
<tr>
<td>$k$</td>
<td>Propagation constant</td>
</tr>
<tr>
<td>$M_S$</td>
<td>Saturation magnetization</td>
</tr>
<tr>
<td>$H_{ex}$</td>
<td>Exchange field</td>
</tr>
<tr>
<td>$M$</td>
<td>Magnetization of FL</td>
</tr>
<tr>
<td>$M_{PL}$</td>
<td>Magnetization of PL</td>
</tr>
<tr>
<td>$H_d$</td>
<td>Demagnetization field</td>
</tr>
<tr>
<td>$\mathcal{E}_{ex}$</td>
<td>Exchange energy</td>
</tr>
<tr>
<td>$H_{PL}$</td>
<td>Magnetostatic field due to PL</td>
</tr>
<tr>
<td>$H_{MN}$</td>
<td>Magnetostatic field due to neighbours</td>
</tr>
<tr>
<td>$w$</td>
<td>Width of the FL</td>
</tr>
<tr>
<td>$U_0$</td>
<td>Barrier height</td>
</tr>
<tr>
<td>$\tau_s$</td>
<td>Spin torque</td>
</tr>
<tr>
<td>$\tau_A$</td>
<td>Ampere torque</td>
</tr>
<tr>
<td>$V^{(j)}$</td>
<td>Volume of $j^{th}$ FL</td>
</tr>
<tr>
<td>$C$</td>
<td>Coupling matrix</td>
</tr>
<tr>
<td>$N$</td>
<td>Demagnetization tensor</td>
</tr>
<tr>
<td>$\tilde{T}$</td>
<td>Transition probability</td>
</tr>
<tr>
<td>$T$</td>
<td>Tunneling probability</td>
</tr>
<tr>
<td>$r_{ij}$</td>
<td>Distance between MTJs $i$ and $j$</td>
</tr>
<tr>
<td>$R$</td>
<td>Radius of the MTJ</td>
</tr>
<tr>
<td>$A$</td>
<td>Area of cross section of MTJ</td>
</tr>
<tr>
<td>$J$</td>
<td>Current density</td>
</tr>
<tr>
<td>$V_{app}$</td>
<td>Applied voltage</td>
</tr>
<tr>
<td>$R_T$</td>
<td>Tunnel resistance</td>
</tr>
<tr>
<td>$V_{thresh}$</td>
<td>Threshold voltage</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Damping constant</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Gyrometric ratio</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Spin transfer efficiency</td>
</tr>
<tr>
<td>$D_x$</td>
<td>Density of states</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Spin of electron (↑ / ↓)</td>
</tr>
</tbody>
</table>