Non-volatile Magnetoresistive Random-Access Memory with semiconductor-based writing/reading channels

M.Sc. Thesis

by

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Non-volatile Magnetoresistive Random-Access Memory with semiconductor-based writing/reading channels

A THESIS

Submitted in partial fulfillment of the requirements for the award of the degree of

Master of Science

by

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Under the guidance of

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CANDIDATE'S DECLARATION

I hereby certify that the work submitted in the thesis **Non-volatile Magnetoresistive Random-Access Memory with semiconductor-based writing/reading channels** is an authentic record of my own work completed under the guidance of **Dr. Alestin Mawrie**, Assistant Professor, **DEPARTMENT OF PHYSICS**, **Indian Institute of Technology Indore**, from July 2023 to May 2024. This work fulfills a portion of the requirements for the award of a Master of Science degree. My thesis has not been submitted for consideration for any other degree from this or any other institution.

Deepak
23/05/2024

Signature of the student with date

(**Deepak Sain**)

This is to confirm that, to the best of my knowledge, the candidate's stated statement is accurate.

23/05/2024

The thesis supervisor's signature and the date

(**Dr. Alestin Mawrie**)

On May 16, 2024, **DeepakSain** successfully completed his oral examination for the M.Sc.

23/05/2024

Signature of supervisor of M.Sc Thesis
Date: 23/05/2024

Signature of Convener,DPGC
Date: 24/05/2024

Dedicated to my family

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Abstract

We proposed a Magnetoresistive Random Access Memory(MRAM) with n-doped AlGaAs/GaAs-based writing/reading channels. We found that the tunable gate voltage in n-doped AlGaAs/GaAs QW (quantum well) is key in designing an efficient and ultrafast MRAM. The Rashba spin-orbit coupling in such QWs can be tuned appropriately by the gate voltage to create an intense spin Hall field which in turn interacts with the ferromagnetic layer of the MRAM through the mechanism of spin-orbit torque. Needless to say, the switching time of the MRAM is also gate tunable. Within the diffisive limit in the QW, the switching time decreases as the Fermi level is tuned towards the bottom of the Rashba band hinting towards an ultrafast n-doped AlGaAs/GaAs semiconductor heterostructure based MRAM. For this reason and for the ease of tuning the switching time, our proposed MRAM is thus a better alternative to the conventional ferromagnetic/spin Hall effect bi-layers MRAM.

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CHAPTER 1

Introduction

Magnetoresistive random access memory (MRAMs)[1, 2] are a class of computing memory which have recently found their applications in several integrated devices. MRAM is non-volatile, low-power-consuming, and fast. A single bit of an MRAM constitutes of the two ferromagnetic layers separated by a non-magnetic layer. The intermediate non-magnetic layer provides a necessary energy barrier to avoid any kind of magnetic interaction between the two ferromagnetic layers. In our design, the magnetization of any layer of a bit can be desirably varied, depending on whether we want to write/read data. The traditional way to provide energy for writing/reading data in an MRAM (*viz.* to switch the magnetic state of a ferromagnetic layer) was so far provided by a magnetic field[3, 4], (which at times becomes too unscalable) until a recent proposal to do it via the mechanism of spin-orbit torque (SOT)[5, 6, 7, 8, 9, 10, 11, 12]. With a SOT[13] based writing/reading channel, an in-plane spin-polarized current from the channel (that interacts with the spin-angular momentum in the ferromagnetic layers) is used to manipulate the magnetization vector in the ferromagnetic layers. The writing channel such as that proposed by V. P. Amin et. al.[5] are Co/Pt, Co/Cu, and Pt/Cu bilayer set up. One of the important properties of the interface of such bilayers is their ability to exhibit the spin Hall effect (SHE) phenomenon. The SHE necessitates a flow of an in-plane spin-polarized charge current (see Fig. [1.1]) which in turn interacts with a ferromagnetic layer of the bit through the mechanism of SOT.

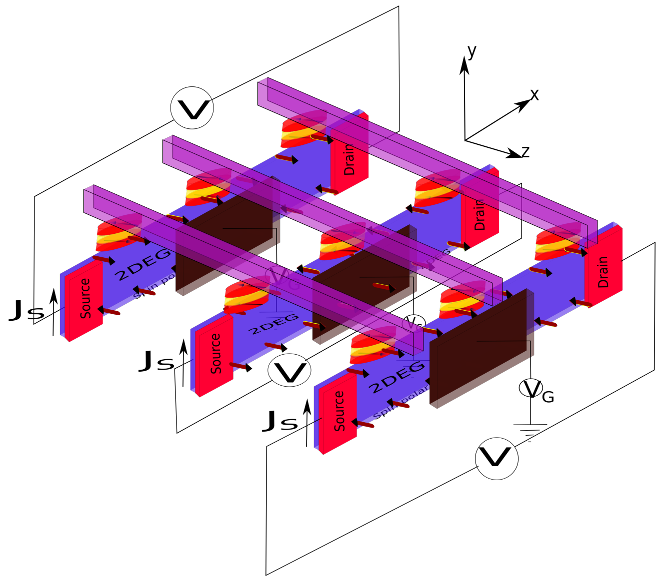

Figure 1.1: Figure showing the schematic of a typical MRAM configuration. The different writing/reading channels shown in the figure are MOSFETs whose channel is made of a spin-orbit coupling dominated 2DEG from the QW in an n-type AlGaAs/GaAs semiconductor heterostructure.

The results presented in this report originate from the idea of "replacing the reading/writing channels in Fig. [1.1] by the semiconductor heterostructure of n-doped AlGaAs/GaAs". The two-dimensional electron gas (2DEG) trapped between the two compound semiconductors in n-AlGaAs/GaAs quantum well is a medium that is well-known for its structural inversion asymmetry (SIA) effect thus providing it, a Rashba spin-orbit coupling (SOC) phenomenon which is at the heart of spin-based devices[14, 15, 16]. The SHE in such quantum well is very well pronounced[17, 18]. The Rashba SOC in the 2DEG has huge influences on various properties such as electronic transport, magnetotransport, magnetization[19, 20], to name a few, and in this case, it should provide the necessary spin Hall field to generate a desired magnetization in the ferromagnetic layers of the bit. Additionally, it is well-known that the SOC strength in these 2DEGs can be manipulated by means of a gate voltage[21, 22, 23, 24, 25, 26, 27], which provides a degree of freedom to tune the spin Hall field. This is unfeasible in the case of a conventional ferromagnetic/SHE bilayers MRAM [5, 6, 7, 8, 9, 10, 11, 12], where the amplitude of the spin Hall field is fixed by the multilayered stack structure.

In this report, we show that our proposed geometry of the MRAM can function as an ultra-fast MRAM simply by applying a proper tuning of the gate voltage to the writing/reading channels. Specifically, there exists an optimal gate voltage applied to the n-doped AlGaAs/GaAs semiconductor heterostructure for which the switching time of the MRAM becomes negligibly small. The reason being, that the spin Hall field provided by the channel when tuned to such gate-voltage becomes fabulously strong to induce the SOT in the (ferromagnetic/n-doped AlGaAs/GaAs) stack structure (as demonstrated in Fig. [1.1]). In the recent experiment[28], the 2DEG at oxide interfaces is used as writing/reading channels, however, the discussion on switching time of the MRAM is still lacking. The switching time of our proposed MRAM would by default be gate tunable, which is another piece of a take-home message.

CHAPTER 2

SHE mechanism in the writing/reading channels:

To have a generic way of describing the QW in a given writing/reading channel, we consider the single particle Hamiltonian for an electron in the QW with an induced gap given by[29, 30, 31, 32]

$$\hat{H}(\mathbf{p}) = \frac{\mathbf{p}^2}{2m^*} + \frac{\alpha}{\hbar}[\boldsymbol{\sigma} \times \mathbf{p}]_z, \tag{2.1}$$

Here, m^* is the effective mass of the electron in the 2DEG, α is Rashba spin-orbit coupling constant and $\boldsymbol{\sigma} = (\sigma_x, \sigma_y, \sigma_z)$ are the (x, y, z) components of the Pauli's matrices. The eigen-system of the above Hamiltonian in the above Eq. [2.1] is given by

$$\left.\begin{aligned} \varepsilon_s(\mathbf{k}) =& \frac{\hbar^2 k^2}{2m^*} + s\alpha k, \\ |+, \mathbf{k}\rangle =& \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ -ie^{i\theta} \end{pmatrix}, \ |-, \mathbf{k}\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ ie^{i\theta} \end{pmatrix}. \end{aligned}\right\} \tag{2.2}$$

with $s = +/-$ denoting the two spin states of the electron . The energy dispersion is demonstrated in Fig. [2.1 a)]. The fixed energy contours for energy $\varepsilon_s(\mathbf{k}) > 0$ and $\varepsilon_s(\mathbf{k}) < 0$, shown in Fig. [2.1 b) & c)], illustrates the eminent spin-orbit coupling in such QWs. We also define the bottom of the Rashba band, $\varepsilon_b = -\varepsilon_\alpha/2$, with $\varepsilon_\alpha = m^*\alpha^2/\hbar^2$ (shown in red dotted line of Fig. [2.1 a)]). This, in-fact is the gate-voltage tunable parameter[21, 22, 23, 24, 25, 26, 27] that we are exploring in this report. In the subsequent section, we shall see that this energy scale will appear in some experimentally measurable quantities such as the spin Hall angle and the switching time. It thus becomes

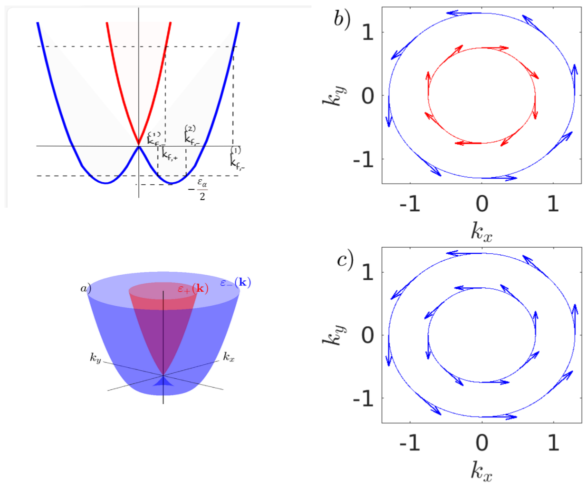

Figure 2.1: a). Plots of the dispersion relation as obtained in Eq. [2.2] with the corresponding magnitude of the Fermi momentum vectors $k_{f,-}^{(1)} = \sqrt{2mE_-/\hbar^2}$, $k_{f,-}^{(2)} = \sqrt{2mE_+/\hbar^2}$ and $k_{f,+} = \sqrt{2mE_-/\hbar^2}$, where $E_\pm = \varepsilon_f + \varepsilon_\alpha \pm \sqrt{\varepsilon_\alpha^2 + 2\varepsilon_f\varepsilon_\alpha}$, with ε_f being the Fermi energy level. The black and green dotted line represent the position of the tunable Fermi energy level. The figure in the subsections b) & c) shows the spin orientation at the Fermi energy contour adjusted at $\varepsilon_s(\mathbf{k}) > 0$ and $\varepsilon_s(\mathbf{k}) < 0$ (denoted by the two types of arrow (red/blue) for the two spin-split states $s = +/-$ in the x-y plane), indicates the spin-orbit coupling in the material.

a defining energy scale in determining the optimum operational condition of the proposed MRAM (as we shall see in the subsequent sections). We are interested in the non-linear dynamic of the spin magnetization vectors in the bit in Fig. [1.1]. The calculation of the magnetization vector through the LLG equation in our system involves a quantity called spin Hall angle, Θ_{SH}. It is defined as the ratio of the spin current density due to the SHE ($j_x^{s_z}$) to the electrical current density (j_e)]. The *calculation of the spin Hall angle*, "Θ_{SH}" is by default based on Eq. [2.1 & 2.2]. For the geometry of our problem, we can also write $\Theta_{\mathrm{SH}} = \sigma_{xy}^z/\sigma_{xx}$, where σ_{xy}^z and σ_{xx} are respectively, the spin Hall conductivity and the longitudinal conductivity of the SOC dominant 2DEG in a writing/reading channel. The two mentioned quantities can be written as

[41, 42, 43, 44, 45, 46]

$$\left.\begin{aligned}
\sigma_{xy}^{z} &= \hbar \iint_{\mathrm{BZ}} \frac{\mathbf{dk}}{(2\pi)^2} \sum_{s} f_{s,\mathbf{k}} \\
&\times \sum_{s' \neq s} \frac{2\mathrm{Im}[\langle s', \mathbf{k}|\hat{J}_x^z|s, \mathbf{k}\rangle\langle s, \mathbf{k}|\hat{v}_y|s', \mathbf{k}\rangle]}{(\varepsilon_s(\mathbf{k}) - \varepsilon_{s'}(\mathbf{k}))^2} \\
\sigma_{xx} &= \frac{e^2}{2}\frac{n}{m}\left[\tau + \left(\frac{n}{n_0}\right)^2 \left(\tau^{tr} - \tau\right)\right],
\end{aligned}\right\} \tag{2.3}$$

where $f_s(\mathbf{k}) = 1/[\exp\{\beta(\varepsilon_s(\mathbf{k}) - \mu)\} + 1]$ is the Fermi-Dirac distribution function, the velocity operator $\hat{v}_{x,y} = \partial\hat{H}/\partial p_{x,y}$ in the x, y direction and $\hat{J}_x^z = \{\sigma_z, \hat{v}_x\}/2$ is the spin-current operator. The energy-dependent lifetime τ and transport time τ^{tr} calculated using full Born approximation, can be written as

$$\frac{1}{\tau} \equiv \frac{n_i m}{\pi\delta}\int_0^{2\pi} d\tilde{\phi}_k \left|\sum_{l=0}^{\infty} T^l(E) e^{il\tilde{\phi}_k}\right|^2 \tag{2.4}$$

$$\frac{1}{\tau^{\mathrm{tr}}} \equiv \frac{n_i m}{\pi\delta}\int_0^{2\pi} d\tilde{\phi}_k \left(1 - \cos\tilde{\phi}_k\right) \left|\sum_{l=0}^{\infty} T^l(E) e^{il\tilde{\phi}_k}\right|^2 \tag{2.5}$$

The calculation of the inverse lifetime and transport time is based on the δ-shell impurity potential $V(r) = v_0 R\delta(r - R)$. This leads to the single impurity Rashba T matrix which can be computed non-perturbatively in the low-energy limit for any circularly symmetric impurity potential. It has the form

$$T^l(E) \equiv \frac{1}{m}\frac{\delta_l^*}{1 + i\delta_l^*/\delta} \tag{2.6}$$

$$\delta_l^* = \frac{m v_0 R^2}{2\,(l!)^2}\left(\frac{(k_0 R)^2}{4}\right)^l \tag{2.7}$$

We again refer back to Eq. [2.3] for calculating the spin-Hall angle. At absolute temperature $T = 0$ K, one can arrive at the following expressions of σ_{xy} as a function of the chemical potential and the gate tunable energy parameter, ε_α, which permits the experimental control over the charge carrier density and the strength of Spin Orbit Coupling.

$$\sigma_{yx}^z = -\frac{1}{4\pi}\frac{e^2}{\hbar} \tag{2.8}$$

A detailed analysis of the above Eqs. [2.8] reveals that for a functioning MRAM, the gate voltage applied to the writing/reading channels should be tuned such that $\frac{n}{n_0} \in [0, 1]$. The variation of the spin Hall angle as a function of the electron density, for this range is shown in Fig. [2.3]. Within the diffusive formulation we found that the spin Hall angle rapidly increases as we tune the Fermi level towards the bottom of the Rashba band. A large spin

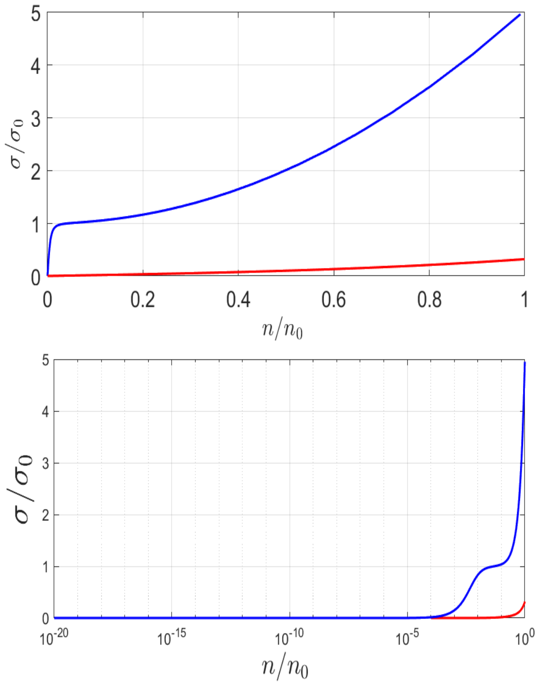

Figure 2.2: The variation of the longitudinal conductivity σ_{xx} with the electron density on a linear(top) and log scale(bottom). The red line is the result from first born approximation and the blue lines is obtained after incorporating the disorders through the self-consistent full Born approximation[48].

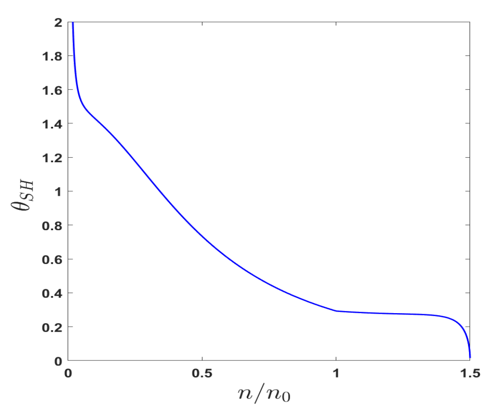

Figure 2.3: The variation of the spin Hall angle as a function of the electron density.

Hall angle indicates a very strong SOT between a writing/reading channel and the ferromagnetic layer of the bit. We thus set the condition $\varepsilon_f = \varepsilon_b$, as the optimum operating condition of the MRAM. In other word, the condition for an ultra-fast MRAM requires the gate voltage (V_G shown in Fig. [1.1]) to be tuned appropriately to meet the said condition. To unveil the switching of magnetisation vector, we have chosen four different values in Fermi energy scale. In the next section, we will understand how this desired magnitude of the gate voltage would lead to a very quick switching time, which is desired for an ultra-fast MRAM.

CHAPTER 3

The magnetization vector in the writing/reading channels:

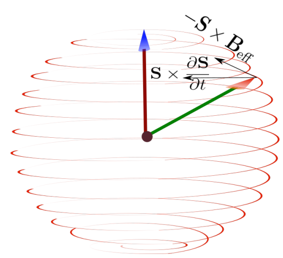

Figure 3.1: Demonstration of the SOT mechanism between the spin vectors in the writing/reading channel and the corresponding ferromagnetic layer.

Having had an understanding of the spin Hall field induced by the writing/reading channels in Fig. [1.1], we now look into the calculation of the magnetization vector in the ferromagnetic layers by using the *Landau-Lifshitz-Gilbert* (LLG) equation. The spin currents in the writing/reading channel (with spin polarization vector $\mathbf{s}$) exert a precession-like spin transfer torque of the form $\propto \mathbf{S} \times (\mathbf{S} \times \mathbf{s})$ on the spin $\mathbf{S}$ of the ferromagnetic layer. The ferromagnetic layer also experiences a damping torque of the form $\mathbf{S} \times \frac{\partial \mathbf{S}}{\partial t}$ (see Fig. [3.1]). The LLG equation can be written as a superposition of these two kinds of torque[5, 35, 36, 37, 38, 39, 40]

$$\frac{\partial \mathbf{S}}{\partial t} = -\gamma \mathbf{S} \times \mathbf{B}_{\text{eff}} + \beta \mathbf{S} \times \frac{\partial \mathbf{S}}{\partial t}. \tag{3.1}$$

Here, $\mathbf{B}_{\text{eff}} = \mathbf{B} + B_{\text{SH}} \mathbf{S} \times \mathbf{s}$ is the effective magnetic field due to the SHE with γ being the absolute gyro-magnetic ratio and in the damping term, β

is the damping constant. The constant $B_{\mathrm{SH}} = \frac{\hbar\Theta_{\mathrm{SH}} j_e V}{2e\mu_s d}$, with Θ_{SH} called as the spin Hall angle [the ratio of the spin current density due to the SHE and the electrical current density (j_e)] and d is the thickness of the ferromagnetic layer. For our design of the MRAM, we set the external applied magnetic field $\mathbf{B} = 0$, since we only depend on the spin Hall field to drive the spin in the ferromagnetic layer of every bit.

For our convenience, we rewrite the same LLG equation as

$$\frac{\partial \mathbf{S}}{\partial t} = -\frac{\gamma}{1+\beta^2}\mathbf{S}\times\mathbf{B}_{\mathrm{eff}} - \frac{\beta\gamma}{1+\beta^2}\mathbf{S}\times(\mathbf{S}\times\mathbf{B}_{\mathrm{eff}}). \tag{3.2}$$

Considering the effective magnetic field $\mathbf{B}_{\mathrm{eff}} = B_{\mathrm{SH}}\mathbf{S}\times\mathbf{s}$ (as stated earlier) and the spin current in the writing/reading channels polarized about the z-axis, $\mathbf{s} = \hat{z}$ (as shown in Fig. [1.1]), we yield the following solution for the different components of the spin vector in the ferromagnetic layer:

$$\left.\begin{aligned} S_x(t) =& S\,\mathrm{sech}\left[\frac{S\gamma B_{\mathrm{SH}}}{1+\beta^2}t+\phi_1\right]\sin\left[\frac{S\gamma\beta B_{\mathrm{SH}}}{1+\beta^2}t+\phi_2\right] \\ S_y(t) =& S\,\mathrm{sech}\left[\frac{S\gamma B_{\mathrm{SH}}}{1+\beta^2}t+\phi_1\right]\cos\left[\frac{S\gamma\beta B_{\mathrm{SH}}}{1+\beta^2}t+\phi_2\right] \\ S_z(t) =& S\tanh\left[\frac{S\gamma B_{\mathrm{SH}}}{1+\beta^2}t+\phi_1\right], \end{aligned}\right\} \tag{3.3}$$

where $S = \sqrt{S_x^2+S_y^2+S_z^2}$ can be regarded as a fixed constant and in our case, we will take $S = 1$. Also, ϕ_1 and ϕ_2 are the constant of integration.

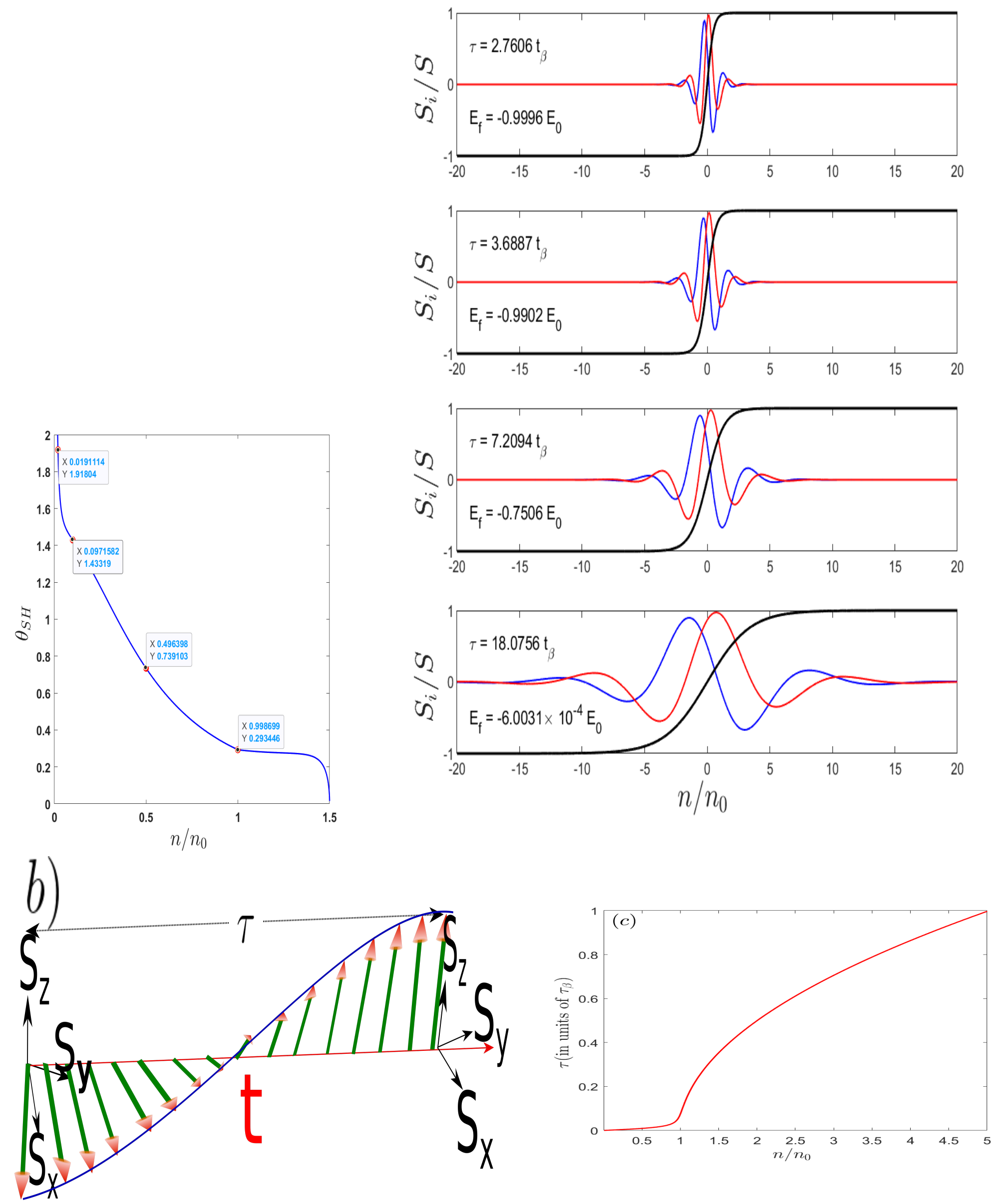

Figure 3.2: a) The variation (S_x, S_y, S_z) components of the magnetization as a function of time which is scaled to $t_\beta = \frac{\Theta_0(1+\beta^2)}{\gamma}$, for different value of electron density as shown in figure(where E_0 is energy at bottom of the band). b) Evolution of the magnetization vector $\mathbf{S} = (S_x, S_y, S_z)$ over a time, τ. c) Plot of the switching time (in units of $\tau_\beta = t_\beta \ln\left[\frac{S+S_z^f}{S-S_z^f}\right]$). Also, we define $\Theta_0 = \frac{2e\mu_s d}{j_e V\hbar}$.

CHAPTER 4

Results and discussions:

It is easy to see from our geometry in Fig. [1.1], that the analysis of the component, $S_z(t)$ is sufficient to determine the switching time of the MRAM, which is the all-important measurable quantity. Before that, let us determine the constant of integration, ϕ_1. We consider the value $S_z(t=0) = S_z^0$, which yields $\phi_1 = \frac{1}{2}\ln\frac{S+S_z^0}{S-S_z^0}$. The variation of the different components of the spin-vector as a function of time is shown in Fig. [3.2 a)], (taking $\phi_2 = \pi/4$ and $S_z^0 = 0$). The different panels in Fig. [3.2 a)] are for [$\varepsilon_f = (-0.44\varepsilon_0, -0.99\varepsilon_0, -0.9998\varepsilon_0, -0.99997\varepsilon_0)$ from bottom to top]. Evidently, as we approach $\varepsilon_f \to \varepsilon_b$, the S_z component of the magnetization vector takes little to no time to switch from [$S_z(t=t_i) = \text{min value}$] to [$S_z(t=t_f) = \text{max value}$], which leads us to the concept of a switching time of the MRAM.

We define the switching time of the MRAM as the time required to turn the magnetization of a given bit from the initial state $S_z(t=t_i) = S_z^i$ (min value) to the desired final state $S_z(t=\tau) = S_z^f$ (max value) (as demonstrated in Fig. [3.2 b)]). In plotting Fig. [3.2 a)], we have assumed that at $t=0$, $S_z(t=0) = S_z^0 = 0$. We can easily obtain the analytic form of the time for the spin component S_z to switch from S_z^0 state to $S_z(t=t_f) = S_z^f$[47]

$$\lambda = \frac{1+\beta^2}{2\gamma B_{\text{SH}}}\ln\frac{(S+S_z^f)(S-S_z^0)}{(S-S_z^f)(S+S_z^0)}. \tag{4.1}$$

These experimental measurements were used in this work to calculate the MRAM switching time.

Table 4.1:

β	Damping Constant	0.011
γ	Gyro-magnetic ratio(rad sec$^{-1}T^{-1}$)	1.76×10^{11}
j_e	Electric current density(A/m^2)	10^{10}
μ	Magnetic moment of elctron(A-m^2)	9.27×10^{-24}
d	Thickness of ferromagnetic layer(nm)	25
V	Volume of ferromagnetic layer(nm^3)	15625
θ_{sh}	Spin Hall angle	1.4549
τ_β		7.67×10^{-14}

Clearly, the switching time becomes $\tau = 2\lambda$, when we set $S_z^0 = 0$. The variation of the switching time as a function of the ratio of the Fermi energy, ε_f is shown in Fig. [3.2 c)]. An ultra-fast MRAM must perceptibly have a negligibly small switching time, strictly speaking, $\tau \to 0$. As evident from the figure, this is easily attainable when the Fermi level is set to the limit $\varepsilon_f \to \varepsilon_b$. Conversely, we can achieve this by taking writing/reading channels with a fixed doping, and by appropriately varying the gate voltage (also seems more practical from the experiment point of view), thus the parameter, ε_α. This luxury of tuning the switching time by means of a gate potential is lacking in the conventional ferromagnetic/spin Hall effect heterostructure MRAM system, in which the amplitude of the spin Hall field at a given current is fixed by the multi-layered stack structure[5, 6].

Conclusion:

In *conclusion*, we have proposed an ultra-fast Magnetoresistive RAM by using the structural inversion assymetric n-doped AlGaAs/GaAs quantum well as writing/reading channels. The very simple idea is to tune the gate voltage applied to the semiconductor heterostructure appropriately, such as to produce a strong spin-orbit Hall field for initiating the spin-orbit torque between the reading/writing channel and a ferromagnetic layer of the MRAM. We have theoretically shown that there exists a desired magnitude of the gate-voltage (such that $\varepsilon_f \to \varepsilon_b$) which brings about a negligibly small switching time of the MRAM. Besides, we have also shown that the MRAM has a variable switching time (again, by means of the tunable spin-orbit coupling). We thus propose that the n-doped AlGaAs/GaAs semiconductor heterostructure should act as a better alternative to the conventional spin Hall effect set-up for functioning as a reading/writing channel of an MRAM. In a nutshell, not only that this work signals the possibility to design an ultra-fast MRAM, but it also suggests the possibility of designing an MRAM with a tunable switching.

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