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# Study of Spin Current & Spin Field-Effect Transistors: A Paradigm Shift in Semiconductor Technology

**Sanjeev Kumar Nirala*, Dr. Deepak Kumar****

*Research Scholar Department of Physics, L.N.Mithila University, Darbhanga
**Assistant Prof. University Department of Physics, L.N.Mithila University, Darbhanga

**Abstract:**

Paul Dirac indeed made significant contributions to physics, especially in merging quantum mechanics with Einstein's theory of relativity. This fusion resulted in the development of relativistic quantum mechanics, unveiling the concept of electron spin among other foundational principles. The exponential growth predicted by Moore's law accelerated the semiconductor and information industries, miniaturizing electronic components and integrating them into everyday devices. However, this rapid advancement faces limitations as transistor sizes approach the Nano-meter scale, reaching a point where a single transistor cannot be smaller than a single atom. Additionally, challenges like Joule heating due to finite-sized electronic devices pose obstacles to further miniaturization. Spin, an intrinsic property of electrons, has been largely disregarded in everyday electronic products, except in specific instances such as magnetic materials or energy band degeneracy. This oversight presents an opportunity for the semiconductor industry through spintronics, a field that aims to leverage electron spin for developing a new generation of electronic devices. The discovery of giant magnetoresistance (GMR) in multilayer ferromagnetic thin films in 1988 marked a significant milestone, opening doors to a new era in electronics and materials science. This discovery introduced a new understanding of magnetoresistance in metals and further fueled the exploration of spin-related phenomena. The field of spintronics not only holds promise for the future of electronic devices but also impacts the information industry and offers new avenues for research in condensed matter physics and material science. Ultimately, despite electron spins being largely ignored in conventional electronics, their potential for revolutionizing technology and scientific understanding is immense.

**Keywords:** Spintronics, Hall effect, GMR, TMR, Spin-orbit Coupling.

**Introduction:**

The interaction of metals with magnetic fields gives rise to phenomena like the Lorentz force and the Hall Effect, which can alter the motion of charge carriers within a sample, subsequently affecting its resistance. When charge carriers experience scattering, their initial velocity determines subsequent cyclotron orbits. Longer relaxation times (lower resistance) tend to amplify the effect on resistance in a magnetic field, typically expressed by MR $\Delta\rho / \rho \propto (H / \rho)2$ (where ρ is resistance and H is the magnetic field).In traditional metals like iron and cobalt, the magnetoresistance (MR) is typically about 0.5-3%. However, a breakthrough occurred in 1988 when Baibich et al. discovered that in FeCr magnetic multilayers, MR could reach up to 50% at 4.2K. This significant increase in MR was due to the arrangement of iron and cobalt layers, their antiferromagnetic coupling, and external magnetic field application, showcasing controllable giant magnetoresistance (GMR). The GMR's key feature is its dependence on the relative orientation of magnetization in ferromagnetic layers, particularly the interlayer thickness. The phenomenon relies on spin-dependent scattering mechanisms, where the mean free path of electrons in ferromagnetic layers varies with the relative orientation of magnetizations, affecting resistance. Subsequently, GMR found applications in magnetic sensors, greatly enhancing sensitivity in detecting magnetization changes. This discovery emphasized the importance of quantum spin in electronic devices and spurred interest in spin-related research. Further advancements led to tunneling magnetoresistance (TMR), surpassing GMR in magnitude and finding extensive commercial applications. Additionally, the discovery of a spin field-effect transistor marked a significant milestone, utilizing spin polarization and spin-orbit coupling in a semiconductor heterojunction to control electron spin orientation. This transistor differed from conventional transistors in that it used gate voltage not just to control current but also to manipulate spin orientation efficiently. The utilization of electron spin for switching ('on' and 'off') instead of merely altering electron motion direction showcased higher efficiency and lower energy requirements. Spintronics, encapsulated by these innovations, relies on spin-polarized carriers or electron spins, coherent spin transport, and the necessary spin coherent time for desired operations. GMR and semiconductor-based spin field-effect transistors stand as key milestones in spintronics development, prompting extensive research and applications. While metallic spintronic devices have seen rapid progress, semiconductor-based spintronic devices offer longer spin coherence lengths, suggesting further potential applications in this domain. Research in spintronics primarily focuses on spin injection, manipulation, and detection, essential for implementing spintronic devices' physical operations efficiently. Spintronics delves into the relativistic quantum mechanics theory, encompassing topics ignored in traditional semiconductor theories. As such, the exploration of spintronics offers opportunities to delve deeper into quantum mechanics while having significant practical implications.

**Methodology and discussions:-** An electron carries an elementary charge *e*. The coherent motion of an electron may circulate an electric current, which can transport energy and information. Though electrons also possess intrinsic spins, the spin orientations of the charge carriers in traditional electronic devices are completely random. It does not exhibit any spin-relevant effect except for trivial degeneracy. Before we introduce the concept of spin current, let us recall how to define electric current in a many-body theory. In principle, the Hamiltonian for the many-body system can be written as

$$H = \sum_{i,\sigma} \frac{1}{2m} \left(P_i - \frac{e}{c} A_\sigma\right)^2 + \sum_{i \neq j} V_{ij}, \quad \text{………………………2.1}$$

Where the first term is the kinetic energy and the second term is interactions between electrons with each other or with the environments. From the Hamiltonian, the velocity operators of electrons are

$$v_\sigma = \sum_i \left(P_i - \frac{e}{c} A_\sigma\right)/m \equiv -\frac{c}{e}\frac{\partial H}{\partial A_\sigma}, \quad \text{……..……………………..2.2}$$

$\sigma = \uparrow,\downarrow$ is the spin index. To define a spin current we introduce a spin-dependent vector potential $A_\sigma$. If we have the energy eigenvalues for the system, $E\,(A_\uparrow, A_\downarrow)$, an electric current is calculated from the formula

$j_e = -e\,(v_\uparrow + v_\downarrow) = -e(\frac{\partial E}{\partial A}\uparrow + \partial E/\partial A\downarrow)$ ………………..2.3

The vector potential $A\sigma$ for an electromagnetic field is conventionally independent of spin, denoted as $A\uparrow=A\downarrow$. Consequently, the electric current is also considered independent of spin, where $v\uparrow=v\downarrow$. This conventionally results in the absence of a spin current. However, if the velocities associated with different spin states ($v\uparrow$ and $v\downarrow$) are unequal—for instance, $v\uparrow=-v\downarrow$—then an electric current may not exist $je \neq 0$), yet ($v\uparrow-v\downarrow) \neq 0$. This difference in velocities is related to the collective motion of electron spin, defining the existence of a spin current. The spin current, defined as $js=\hbar/2(v\uparrow-v\downarrow)$ for a spin unit of $\hbar/2$, is contingent upon both the direction of motion and the spin polarization of electrons. In systems where the vector potential is spin-dependent $A\uparrow \neq A\downarrow$), it's plausible for the system to exhibit a circulating spin current.

The spin-dependent vector potential emerges from the physical origin of electron spin, which is a relativistic quantum effect elucidated by Dirac theory. The interaction between electron spin and magnetic fields, known as Zeeman energy splitting, arises from the intrinsic properties of electron spin in an electromagnetic field. Spin-orbit coupling is another manifestation of this effect.

In atomic physics, spin-orbit coupling is understood in a classical sense: as an electron orbits around a nucleon carrying a positive charge, the moving nucleon generates a ring-like electric current. According to the Biot-Savart law, this current induces a perpendicular magnetic field on the electron, leading to the spin-orbital coupling effect.

$$\Delta V = \frac{1}{2m^2c^2}\frac{1}{r}\frac{\partial V}{\partial r}\vec{S}\cdot(\vec{r}\times\vec{p})$$
$$= \frac{1}{2m^2c^2}(\nabla V\times\vec{p})\cdot\vec{S},$$

…………………2.4

In relativistic quantum mechanics, this effect emerges from the interference between electrons and positrons, incorporating a factor of $2mc2$ reflecting the energy gap between electrons and positrons (about 1 MeV). While this effect is usually tiny in single atoms, it becomes amplified in certain crystal systems. Crystal electrons in solids, due to their periodicity, form band structures in reciprocal vector spaces. In systems lacking certain inversion symmetries, spin-orbit coupling near specific regimes gets magnified. For instance, in a two-dimensional electron gas of certain heterostructures, such as InGaAs/InAlAs, strong coupling (Rashba spin-orbit coupling) occurs near the Gamma point, characterized by a coupling coefficient of order $10-4c$ (where $c$ is the speed of light). This coupling is inversely proportional to the energy gap between conduction and valence bands in semiconductors, and it has been observed experimentally, manifesting as an energy splitting in such systems.

Overall, spin-orbit coupling, arising from relativistic quantum effects and amplified in specific crystal systems lacking certain symmetries, contributes significantly to the behaviour of electrons in electric and magnetic fields, leading to the potential emergence of spin currents under certain conditions.

$$\vec{v} = \frac{1}{m}\left(\vec{p} + \frac{e}{c}A_\sigma\right),$$ …………………… …2.5

$$(\vec{A}_\sigma = \lambda\frac{mc}{e}\hat{z}\times\vec{\sigma}).$$ …………………………..2.6

We observe that the coupling will generate a spin-dependent vector potential [17]. From the definition of spin current, this vector potential makes it possible to circulate a spin current. A spin current is a second-rank pseudo tensor,

$$J_s^\alpha = \frac{\hbar}{2}\{\sigma^\alpha, v\}$$ ………………………………….2.7

Absolutely, understanding the physical effects and properties of spin current is crucial, particularly in the context of its potential applications in devices. The unique properties of spin current, including its non-conservation and its dependence on spin orientation, make it an intriguing subject in condensed matter physics.

A notable difference between spin current and electric current lies in their behaviour under time reversal. In a time reversal operation where $t\rightarrow-t$, the velocity $v\rightarrow-v$ and the charge $e\rightarrow e$. Consequently, an electric current $je=-ev$ changes its sign ($je\rightarrow-je$). However, in the case of a spin current, where the spin ($\sigma\rightarrow-\sigma$), the spin current ($js\alpha\rightarrow js\alpha$) remains invariant. This property hints at the potential for low dissipation or even dissipative-less behaviour associated with spin currents, as the time-reversal symmetry remains intact.

However, the dissipative behaviour of spin currents remains an open question. While spin current induced by electric current in the Spin Hall Effect exhibits less dissipation, the nature of dissipative behaviour in spin currents itself is not yet fully understood.

Spin currents, unlike electric currents, are not conserved due to the non-conservation of electron spin in solid materials. Conservation laws in physics are typically governed by symmetries. For instance, translational invariance leads to the conservation of momentum, while U(1) symmetry results in the conservation of current. Various mechanisms, such as magnetic impurities scattering, spin-orbit coupling, and nuclear spin, can break the conservation of spin current, sparking debates on its precise definition and physical relevance.

Despite the challenges in conservation and transport over long distances due to spin decoherence, recent experimental progress indicates the tunability of spin coherence length using external fields or along specific axes in materials. This presents opportunities for material scientists to explore materials with extended spin coherence lengths, potentially enhancing the viability of spin current-based applications.

The Spin Hall Effect, among other phenomena, has significantly contributed to understanding spin current's general properties, making it an essential focus in condensed matter physics research. The investigations into the physical effects and behaviour of spin current pave the way for potential applications in mesoscopic devices and circuits, emphasizing the importance of comprehending its fundamental properties for practical implementation.

**ELECTRIC FIELD INDUCED BY SPINCURRENT:-**

By Biot-Savart law, a pure spin current can indeed induce an electric field associated with the movement of electron spins. When electrons possess spin, they also have a magnetic moment due to their intrinsic spin. Consequently, a spin current also carries with it a magnetic moment current.

It's a well-established principle that a single moving magnetic moment behaves equivalently to an electric dipole. Therefore, a moving magnetic moment has the potential to induce an electric field.

One way to estimate this induced electric field is to consider the spin current as comprising positive and negative "magnetic charges" (analogous to magnetic monopoles) moving in opposite directions within the current. When these charges are assumed to be extremely close together and their magnitude tends toward infinity ($\delta \rightarrow 0+$ and $q_{mc} \rightarrow +\infty$), they can be seen as forming a magnetic dipole moment $m\rightarrow = q_{mc}\delta_m$^ (where m^ denotes the polarization direction). Consequently, the collective spin current can be conceptualized as a group of moving magnetic dipoles.

Each of these magnetic dipoles formed by the spin current can generate a magnetic field. Under the Lorentz transformation, this magnetic field can be transformed into an electric field. This reasoning leads to the conclusion that a pure spin current, akin to a collection of moving magnetic dipoles, has the potential to induce an associated electric field in the surrounding space.

$$\vec{E} = \int \frac{\mu}{4\pi} J_m dV \times \frac{1}{R^3} \left( \hat{m} - \frac{3\vec{R}(\vec{R} \cdot \hat{m})}{R^2} \right). \quad \text{………………..2.8}$$

This field is very small but still measurable

Certainly! While an electric current experiences a transverse Lorentz force in a magnetic field, similarly, a spin current can experience an analogous force in an electric field. This effect arises due to spin-orbit coupling, where a quantum mechanical anomalous velocity contributes to the emergence of a force dependent on both spin and the external electric field.

In a non-relativistic quantum framework, the spin-orbit coupling contributes to an anomalous velocity, denoted by δv→ = e/4m^2c^2 σ→ × ε→, where ε→ is the electric field. This leads to a force exerted on the spin current, expressed as F→ = ħ/4 {v→, σ→ · ε→ / ε}. Similar to the Lorentz force experienced by electric currents in a magnetic field, this force is proportional to the square of the electric field.

While this force on a free electron might be minute, for controlling electron spins, its effect becomes more significant and can result in measurable consequences. For instance, this force contributes to phenomena like zitterbewegung, observed in Dirac particles.

The enhanced spin-orbit coupling due to band structures in semiconductors compared to a free Dirac electron enables observable effects. Systems like Rashba systems, represented by $H_R = \lambda(p_x\sigma_y - p_y\sigma_x)$, demonstrate spin transverse forces that manifest within specific configurations of electron motion.

Moreover, a consequence of spin current is spin accumulation near physical boundaries. Unlike charge accumulation inducing electric fields or forces, spin accumulation relies on the diffusion process to reach equilibrium. The spin diffusion length and spin relaxation time play vital roles in spin accumulation.

A continuity equation governs the spin current and spin density distribution, highlighting the spin torque density as a key factor. Near boundaries, the spin current vanishes, leading to non-uniform spin density distribution. Spin-dependent chemical potential and the diffusion equation describe this spin diffusion process, with the spin density decaying exponentially with distance.

These aspects underline the intricate relationship between spin currents, spin accumulation, and their behaviour in the presence of external fields, boundary conditions, and material properties, particularly in systems influenced by spin-orbit coupling.

**References:-**

1. S. Datta and B. Das, *Appl. Phys. Lett.* **56**, 665 (1990).
2. J. Schliemann, J.C. Egues, and D. Loss, *Phys. Rev. Lett.* **90**, 146801 (2003).
3. S. Bandyopadhyaya and M. Cahay, *Physica E* **25**, 399 (2005)
4. C. Wang, J.P. Snyder, and J.R. Tucker, *Appl. Phys. Lett.* **74**, 1174 (1999).
5. E. I. Rashba, *Phys. Rev. B* **62**, R16267 (2000).
6. A. Kinoshita, Y. Tsuchiya, A. Yagishita, K. Uchida, and J. Koga, 2004 Symp. on VLSI Technology, Digest of Technical Papers, 2004, Honolulu, USA, 15–17 June 2004, pp. 168–169.
7. Gupta J. A., Peng X., Alivisatos A. P., Awschalom D. D., *Phys. Rev. B* ***59***, R10421 (1999).
8. Flatté M., Byers J., *Phys. Rev. Lett.* ***84***, 4220 (2000).**95**
9. Ohno Y., et al., *Phys. Rev. Lett.* ***83***, 4196 (1999).**96**
10. Malajovich I., et al., *Phys. Rev. Lett.* ***84***, 1015 (2000).**97**
11. Malajovich I., et al., *Nature* ***411***, 770 (2001).
12. Beschoten B., et al., *Phys. Rev. B* ***63***, R121202 (2001).
13. Crooker S. A., et al., *Phys. Rev. Lett.* ***75***, 505 (1995).
14. R. Fiederling *et al.*, *Nature***402**, 787, (1999).**01**
15. Jonker B. T., et al., *Phys. Rev. B* ***62***, 8180 (2000).**2**
16. Ohno Y., et al., *Nature* ***402***, 790 (1999).**3**
17. Koshihara S., et al., *Phys. Rev. Lett.* ***78***, 4617 (1997).
18. DiVincenzo D. P., et al., *Nature* ***408***, 339 (2000).
19. Kikkawa J. M., Awschalom D. D., *Science* ***287***, 473 (2000).
20. Salis G., et al., *Phys. Rev. Lett.* ***86***, 2677 (2001).
21. Kawakami R. K., et al., *Science* ***294***, 131 (2001).
22. Loss D., DiVincenzo D. P., *Phys. Rev. A* ***57***, 120 (1998).
23. Burkard G., Engel H., Loss D., *Fortschr. Phys.* ***48***, 965 (2000).**0**
24. Engel H.-A., Loss D., *Phys. Rev. Lett.* ***86***, 4648 (2001).
25. A. Imamoglu *et al.*, *Phys. Rev. Lett.***83**, 4204, (1999).**12**
26. Bonadeo N. H., et al., *Science* ***282***, 1473 (1998).**3**
27. Paillard N., et al., *Phys. Rev. Lett.* ***86***, 1634 (2001).
28. Gupta J. A., et al., *Science* ***292***, 2458 (2001).**5**

29. Kane B., *Nature **393***, 133 (1998).

30. R. Vrijen *et al.*, *Phys. Rev. A***62**, 012306, (2000).**7**

31. Gordon J. P., *Phys. Rev. Lett. **1***, 368 (1958).**8**

32. Korotini M. A., et al., *Phys. Rev. Lett. **80***, 4305 (1998)

33. Kikkawa J. M., et al., *Physica E **9***, 194 (2001

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