Parametric Investigation and Survey of Spintronic Sensors v-s Electronic Sensors (Case study: Current sensors)

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ABSTRACT

Conventional electronic devices depend on the transport of electrical charge carriers–electrons in a semiconductor such as silicon [1]. Now, however, physicists are trying to exploit the 'spin 'of the electron rather than its charge to create a remarkable new generation of spintronic devices which are smaller, more versatile and more robust than those currently making up silicon chips and circuit elements. Compared with other solid-state sensors, spintronic sensors offer more sensitivity and precision and are not damaged by large magnetic fields. This paper presents the investigation results of the comparison of the conventional electronics current sensors and spintronics current sensors relying on the sensitivity of the two. To extract our conclusion survey of the researches on spintronics sensors and conventional electronic sensors are done separately.

Keyword: Conventional electronics, spin, GMR, current sensor, Magnetic Bipolar Transistor

INTRODUCTION

Existing semiconductor electronic and photonic devices utilize the charges on electrons and holes in order to perform their specific functions such as signal processing or light emission.

Spintronics, also called magneto-electronics or spin-electronics is a branch of physics engaged with the storage and transfer of information by active manipulation of electron spins in addition to electron charge, to process electronic data in solid-state systems [4].

Like any other conventional electronics equipment, electronic sensors as well, are relatively large in size and consequently their cost is large. In addition, their operation need substantial amount of power. To overcome this, industry continues to reap the benefits of solid state magnetic field sensing. Every day new applications are found for solid state magnetic field sensors due to their small size, low power and relatively low cost. This brings the spintronics technology in to application.

THEORETICAL BACK GROUND

Spin and Spintronics

An electron has two attributes, "charge" and "spin". Spin is an intrinsic quantity of the angular momentum of electrons, treated as if they were tiny spinning balls [5], as shown in Fig.1.below.

In today's world of computers which is based on conventional electronics, we have either an ON or OFF, (1 or 0) or (UP or DOWN) state, the in-between states being ignored. But in spintronics with the spin of electron we can have many states and the two states limitation can be overcome. For this reason, in spintronics, large amount of information can be processed a whole lot faster. The relative number of electrons with spin-up and spin-down is very important for the magnetic properties of a chosen material. Nonmagnetic materials are characterized by the same number of electrons having the same properties in both (up/down) spin channels, while in magnetic materials there is an imbalance in the density of states for spin-up and spin-down electrons [6].

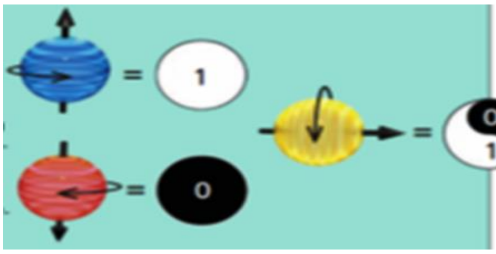

Fig. 1. Quantum representation of Spin [5]

Among recent advances in spintronics, magnetic tunnel junctions have been under intensive study and are poised to become one of the most widely used spintronic devices.[7].

Successful application of the wide range of possible spin dependent phenomena in semiconductor systems requires: effective and efficient techniques for electrical injection of strongly spin-polarized currents, transfer of electrons without losing their spin, as well as electrical detection of such spin current.

2.2. Basic Electronics and Spintronics Devices Modeling

i). Conventional P-N Junctions: Conventional spin-unpolarized p-n junctions are semiconductor material whose left side is p-type, doped with N_a acceptors per unit volume, and whose right side is n-type, doped with N_d donors per unit volume. At V = 0, the generation current j_{gn} due to thermal excitation of an electron-hole pair, and the recombination current j_{rn}, due to the thermal activation of the electrons are in equilibrium, i.e., $j_{gn} = j_{rn}$ and there is no net currents flow [8]

$$j_{gn} = -j_{rn}\,(V = 0) = -KN_d\left(e^{-qV_b/K_BT}\right) \quad (1)$$

$$j_n = j_{gn} + j_{rn} = j_{gn}\left(e^{qV_b/K_BT} - 1\right) \quad (2)$$

$$j_p = j_{gp} + j_{rp} = j_{gp}\left(e^{qV_b/K_BT} - 1\right) \quad (3)$$

Where: K is constant, N_d-density of electrons, q - magnitude of the electron charge, V_b- threshold voltage, T-temperature, k_B – Boltzmann's constant. j_{gn} and j_{rn} are the generation and recombination currents due to electrons respectively, and j_{gp} and j_{rp} are the generation and recombination currents due to holes respectively. j_n and j_p are the electron and hole current densities respectively.

Putting electrons and holes together, we finally obtain the I-V characteristic equation of a p-n junction in the form,

$$j = j_g\left(e^{qV_b/K_BT} - 1\right) \quad (4)$$

where j is the current density in the p-n junction and

$$j_g = j_{gn} + j_{gp}$$

ii). Magnetic diode: At the junction of magnetic and non- magnetic semiconductors there is a source of non-equilibrium spin in the junction. The source can be either electrical or optical. For simplicity we consider only one type of magnetic diodes, those with magnetic p-region. We further assume that holes are spin unpolarized, since holes, due to their strong spin-orbit coupling, usually lose their non-equilibrium spins very fast in comparison to electrons.

The generation current is different for spin-up and for spin-down electrons. The same is true for the recombination current. This current can be controlled by magnetic field, modifying the splitting of the electron bands in the magnetic region, or by introducing non-equilibrium spins in the n-region. [8].

The electron recombination current, jrn, in the magnetic diode is jrn↑+jrn↓ where jrn↑ is the recombination current of the spin-up electrons and jrn↓ is the recombination current of the spin-down electrons.

Suppose the equilibrium spin polarization of electrons in the p-region is P_0, and the non-equilibrium spin polarization in the n-region, due to a spin source, is δP. Then the spin-up and spin-down electron currents are [8],

$$j_{rn}\uparrow = 1/2\ K\,(1 + P_0)\ (1 + \delta P)\,N_d\left(e^{q(-V_b+V)/K_BT}\right) \quad (5)$$

$$j_{rn}\downarrow = 1/2\ K\,(1 + P_0)\ (1 + \delta P)\,N_d\left(e^{q(-V_b+V)/K_BT}\right) \quad (6)$$

where all the parameters are as defined in the previous discussion.

The generation current does not depend on non-equilibrium conditions. This means that,

$$j_{gn}\uparrow = -j_{rn}\uparrow\ \ (V = 0, \delta P = 0) = -\ 1/2\,K\,(1 + P_0)\,N_d\left(e^{qV_b/K_BT}\right) \quad (7)$$

$$j_{gn}\downarrow = -j_{rn}\downarrow\ (V = 0, \delta P = 0) = -\ 1/2\,K\,(1 + P_0)\,N_d\left(e^{qV_b/K_BT}\right) \quad (8)$$

Summing up all the contributions to the electron current we obtain [8],

$$j_e = j_{gn}\left[e^{qV_b/K_BT}(1 + P_0\delta P) - 1\right] \quad (9)$$

The above equation expresses spin-charge coupling in magnetic p-n junctions [8]. For a parallel orientation of the spins, the current is enhanced; and for an antiparallel orientation, the current is reduced. The relative change of the current with respect to the orientation of the equilibrium and non-equilibrium spin gives rise to a giant magneto resistive (GMR) effect in magnetic diodes. The current is either positive or negative, depending on the sign of the product of $P_0\delta P$. This phenomenon is called spin-voltaic effect producing an emf from non-equilibrium spin [8]. The spin-voltaic effect is illustrated in Fig. 2. It demonstrates the way how to make the current in a magnetic diode larger or smaller. Referring Fig.2 below, if we look at the potential barrier going from the n- to p-region, we see that by making the spin in the n-region non-equilibrium, pointing-up electrons, will have a lower barrier to cross, increasing the recombination current. On the other hand, introducing more spin-down electrons in the n-region, electrons have to climb a higher barrier, reducing the recombination current. Since the generation current is not influenced by the non-equilibrium properties, the current for the parallel orientation will be larger than that for an antiparallel orientation of the equilibrium and non-equilibrium spins [8].

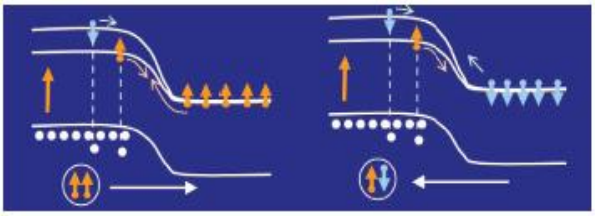

Fig. 2. Spin-voltaic effect in a magnetic diode [8].

iii). Conventional Bipolar Junction Transistor: In a conventional transistor, say n-p-n type, when a voltage is placed across the gate, free electrons either are attracted towards the gate (base) or away from it, depending on the direction of the applied voltage. This lack or presence of gate electrons controls the flow of current between emitter and collector, allowing the transistor to occupy ON or OFF states [9].

The problem with conventional transistors is their volatility. When power is shut off, the electrons in the p-type semiconductor are no longer confined to a single region and diffuse throughout, destroying their previous ON or OFF configuration. This volatile effect can be avoided by introducing, a new type of transistor known as magnetic transistor [9].

iv). Magnetic bipolar transistor:

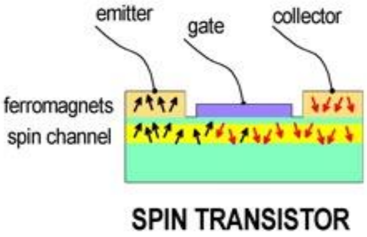

Fig 3. Magnetic Transistor.

In a magnetic transistor Fig. 3, magnetized ferromagnetic layers replace the role of n and p-type semiconductors. As in a conventional field effect transistor there is a third electrode (gate) that generates an electric field to modulate the current in the transport channel. The magnetizations of injector and detector are assumed to be parallel [10]. In case of zero gate voltage, every electron emitted from the injector with its spin oriented along the magnetization direction enters the detector with no change to spins during transport. For nonzero gate voltage the gate electrode produces an electric field that causes the spins to process. Substantial current can flow through parallel magnetized ferromagnetic layers. However, if, say, in a three layer structure, the middle layer is antiparallel to the two outside layers, the current flow would be quite restricted, resulting in a high overall resistance.

PARAMETRIC INVESTIGATION AND SURVEY OF CURRENT SENSORS

Current sensors are electrical devices which measure currents in a cable or a wire and generate a signal of some sort in response to the current. In most electrical device current monitoring is more meaningful compared to voltage monitoring because current signal contain much valuable information such as harmonics, unbalanced load in electric power distribution systems, unbalanced forces and motor / bearing irregularities in motor drive train traction system. In addition to this, current sensors are widely used as feedback devices in field industrial equipment, power system protection, and various test-controlled systems [11].

We may classify current sensors as the conventional current sensors and spintronics current sensors. The conventional current sensors include traditional current transformers, resistive shunt, Rogowski current sensors, fluxgate current sensors, and Hall effect current sensors. And the spintronics current sensors include: AMR (Anizotropic Magneto-Resistnce) current sensors, and GMR (Giant Magneto-Resistance) current sensors or (spin valve current sensors) [12][13] .

Sensor parameters

Sensor's parameters characterize its performance as a sensor. The performance of the current sensors consists of static, dynamic and thermal characteristics, and determines its application. The static characteristics include the sensor's range, sensitivity, offset voltage, linearity and accuracy while a dynamic characteristic consists of the frequency response of the sensor, the amplitude response and the phase response of the sensors. Since sensitivity is the most important figure of merit for all sensors the paper considers only this performance parameter.

In this work, sensitivity is understood as, the smallest absolute amount of change that can be detected by a measurement.

Parametric investigation of Electronics current Sensors

Hall Effect integrated circuits are used in a wide range of applications, like in computers, automobiles, aircraft, and medical equipment etc. It is possible to construct high-quality Hall-effect transducers with the standard integrated circuit processes and by integrating it to auxiliary signal-processing circuitry, on the same silicon die; usable sensors can be fabricated [14]. Because of the above reasons, among different electronics current sensors, we focus and investigate the researches done on Hall Effect current sensors.

In the first survey we see the research which aims to prove the combined Hall sensors and coils to obtain a wideband, CMOS-compatible, contactless current sensor. This study fabricated orthogonally-coupled normal n-well; normal n-well with 45° orientation; p+ doping pinched n-well and poly gate covered n-well Hall sensor

Table 1 Summarized electronics current sensor investigation table

survey	**Material used**	**Result**	
		Sensitivity	
		A	*B*
Survey-1 [20]	p-substrate, N-well implantation and p+ doping	113.13 V/AT	116.94 V/AT
		115.27 V/AT	119.51 V/AT
		113.63 V/AT	117.65 V/AT
		115.42 V/AT	119.53 V/AT
		108.36 V/AT	114.07 V/AT
		117.24 V/AT	121.14 V/AT
		114.15 V/AT	117.95 V/AT
		113.40 V/AT	118.04 V/AT
Survey-2 [22]	p-substrate, N-well implantation and p+ diffusion	80.7 V/AT	
Survey-3 [23]	N-type Epi Resistance (InGaAs/InP: Si[100]), P-type Well Resistor, P+ Resistor	19.9 uV/G/single hall plate/Ceramic package/160µm	
		17.1 uV/G/single hall plate/plastic package/160µm	
		19.6 uV/G/Quad hall plate/ceramic package/160µm	
		17.0 uV/G/Quad hall plate/plastic package/160µm	
		18.3 uV/G/single hall plate/Ceramic package/50µm	
		15.6 uV/G/single hall plate/plastic package/50µm	
		15.4 uV/G/Quad hall plate/ceramic package/50µm	
		19.9 uV/G/quad hall plate/plastic package/50µm	
Survey-4 [21]	substrate δ-doped GaAs, 6000Å Buffer δ -doped GaAs, 120Å Channel δ -doped $In_{0.18}Ga_{0.82}As$, 50Å Spacer δ -doped $Al_{0.35}Ga_{0.65}As$, 200Å supply $Al_{0.35}Ga_{0.65}As$ and 50Å Cap GaAs	8 mV/mT	

	substrate δ-doped GaAs, 6000Å Buffer δ-doped GaAs,Channel δ-doped $In_{0.15}Ga_{0.85}As$, Spacer δ-doped 50 Å $Al_XGa_{(1-X)}As$, supply $Al_XGa_{(1-X)}As$ and 100Å Cap GaAs	16 V/μT

prototypes. As the result different values of sensitivity are obtained in each prototype in different sizes

The research of the second survey targets to investigate the effect of sensitivity of the Hall Effect current sensor with biasing current and temperature. The result of the research declares sensitivity to have linear relation with biased current and temperature. The third survey assesses the research which focuses on the effect of stress on the sensitivity. This research utilizes two 160μm and 50μm side length Hall plates with one quad Hall plate, and with two single Hall plates in each size encapsulated in plastic and ceramic packages. As a result different values of sensitivity are obtained. The research discussed in the fourth survey focused on the way of avoiding offset and noise, improve sensitivity and reduce the power conception of the Hall Effect current sensor. The research design is categorized in to DC and AC Linier Hall Effect sensors and obtains two improved sensitivity results as compared to the other similar types of current sensors.

Spintronics current Sensor

The whole GMR effect sensor system contains three main subsystems: The sensing head which is used to convert the measured current signal to the voltage signal. The signal processing subsystem which helps to process the voltage signals of the sensing head output and calculate the measured current. The power supply subsystem to provide the power source for the whole sensor system. In the design of the GMR chip, in order to convert the magnetic signal to a voltage signal, four identical spin-valve resistors making up a Wheatstone bridge are used Fig. 4. In the bridge circuits two of the resistors are sensing resistors; the other two are reference (Shield) resistors.

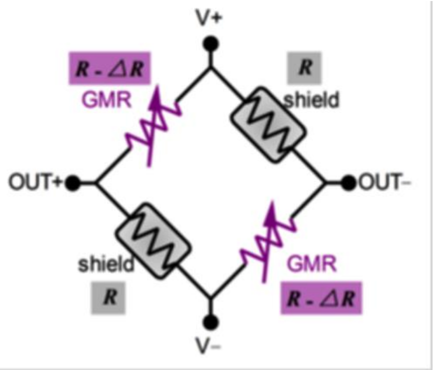

Fig. 4. Wheatstone bridge of GMR chip [15].

Parametric investigation of Spintronics current Sensors

In this section, the research on a Spintronics current sensors based on GMR effect are investigated. As per the investigation, it is found that, the performance parameters of the current sensor varies depending on the material, the size and the number of magneto-resistive elements used per bridge resistor.

In the first survey the research under investigation uses serial and parallel configurations with 10 cm and 100 μm width of the current strap respectively. The result shows that the sensitivity in both cases is similar; however the power consumption is found different. The study of the second survey presents three different configurations, with one, three, and seven magneto-resistive elements per bridge resistor. The study obtains three different sensitivity results which are relatively close to each other and it concludes that sensitivity doesn’t improve much with increasing impedance. In the third survey the assessed research studied the feasibility of spin-valve sensors when working in high-frequency power electronics applications. As a result it is reported that with application of as large current as, (up to 10A) good sensitivity is observed, but the accuracy obtained is degraded. In the fourth survey uncoupled hard and soft-magnetic layers are used, and field is applied repeatedly, and the study shows the sensor performance is affected strongly at the beginning; indeed no further change observed. The summarized results of the researches are presented in the table below.(Table 2)

RESULT COMPARISON

Each of the above summarized sensitivity data of spintronics and conventional electronics current sensors have different units. To simplify the comparison it needs to change in to identical unit of measurement.

For example, in the electronics current sensors first survey, the value of sensitivity of the first sample under category A is $113.13\frac{V}{AT}$. To convert in to $\frac{V}{T}$ we should multiply by the 2A DC biased current used during sensitivity measurements.

Therefore:

$$113.13\left(\frac{V}{AT}\right)\times 2A \;= 226.26\left(\frac{V}{T}\right)$$

If we take sample S_1 of the second survey of spintronics current sensors the sensitivity value is $0.86\frac{mV}{VmA}$ at 1mA biased current per 20 (Oe) of magnetizing field using 5mV.

Table 2 Summarized spintronics current sensor investigation table

survey	Sensor code	Material used	Sensitivity Result
Survey-1 [16]	SV07-SN (10cm)	Si / SiO2 (1500Å) Substrate; Ta (20 Å) Buffer; NiFe (30 Å) and CoFe (20 Å) Free layer; Cu (22 Å) Separator; CoFe (20 Å) Pinned layer; MnIr (60 Å) Ferromagnetic/ Antiferromagnetic layer and Ta (40 Å) Passivation Layer	< 0.5 nTesla/√HZ or < 1 Oe/mA
	SV07-PW (100µm)		< 0.5 nTesla/√HZ or < 1 Oe/mA
urvey-2 [17]	S-1	Si / SiO2 (1500Å) Substrate; Ta (20 Å) Buffer; NiFe (30 Å) and CoFe (20 Å) Free layer; Cu (22 Å) Separator; CoFe (20 Å) Pinned layer; MnIr (60 Å) Ferromagnetic/ Antiferromagnetic layer and Ta (40 Å) Passivation Layer	0.86 forDC, 0.87 ±0.1 for AC) mV/(V mA)
	S-2		**0**.81 forDC, 0.87 ±0.1 for AC) mV/(V mA)
	S-3		0.79 forDC, 0.87 ±0.1 for AC) mV/(V mA)
Survey-3 [18]	-	Si / SiO2 (1500Å) Substrate; Ta (20 Å) Buffer; NiFe (30 Å) and CoFe (20 Å) Free layer; Cu (22 Å) Separator; CoFe (20 Å) Pinned layer; MnIr (60 Å) Ferromagnetic/ Antiferromagnetic layer and Ta (40 Å) Passivation Layer	0.91 mV/ (V.Oe)
Survey-4 [19]	-	Si Substrate; Fe Buffer; CoFe Free layer; Cu (> 2 nm) Separator; CoFe Pinned layer; Co_x Cu_1 $_{nm}Co_y$ $Cu_{1\,nm}Co_x$ Ferromagnetic/ Antiferromagnetic layer and Fe Passivation Layer	2 mV V^{-1} (kA $m^{-1})^{-1}$

where (Oe --- in Ampere /Meter) known as Oersted, is a magnetic field strength unit.

Now to convert in to $\frac{V}{T}$

$$0.86\left(\frac{mV}{VmA}\right)\times 1mA \;= 0.86\left(\frac{mV}{V}\right)$$

Dividing by the field

$$\frac{0.86\frac{mV}{V}}{20(Oe)} = 0.043\left(\frac{\mathrm{mV}}{\mathrm{V\,(Oe)}}\right)$$

$$1\,(Oe) \;= \frac{10^3}{4\pi}\left(\frac{A}{m}\right)$$

And

$$1G = \frac{10^3 A}{m}$$

, where G is - Gauss

Therefore

$$1(Oe) \;= \frac{1}{4\pi}G$$

Also

$$1G = 10^{-4}T$$

So

$$1(Oe) = \frac{10^{-4}}{4\pi}T$$

$$\left(\frac{0.043}{\frac{10^{-4}}{4\pi}}\right)\frac{\mathrm{mV}}{\mathrm{VT}}$$

$$\left(\left(\frac{0.540}{10^{-4}}\right)\times\left((10^{-3}\right)\right)\left(\frac{V}{VT}\right) = 5.40\frac{V}{VT}$$

Multiplying by the used voltage amount, we obtain

$$\left(5.40\left(\frac{V}{VT}\right)\right)\times\left((5\times 10^{-3})V\right) = 0.027\left(\frac{V}{T}\right)$$

All other data units are converted in similar fashion, but depending upon the units, the way of conversion and the units used for conversion may be different. The converted results are presented in the table below. Table 3 Result comparison table

Sensor Technology	Sensitivity(V/T)	Range of sensitivity (V/T)
Electronics Current Sensor (Hall Effect)	226.26	(0.154-242.28)
	233.880	
	230.540	
	239.020	
	227.260	
	235.300	
	230.840	
	239.060	
	216.720	
	228.140	
	234.480	
	242.280	
	229.000	
	235.900	
	226.800	
	236.080	
	0.560	
	0.199	
	0.171	
	0.196	
	0.170	
	0.183	
	0.156	
	0.154	
	0.199	
	8.000	
Spintronics Current Sensor (spin Valve)	0.027	(0.004-3.431)
	0.127	
	0.049	
	0.136	
	3.431	
	0.004	

We notice that sensitivity is defined as the smallest absolute amount of change that can be detected by a measurement. The result obtained from the sensitivity study is presented in the form of table and graphs. As we see from the table III above the range of the sensitivity of the spintronics sensor is 0.004 to 3.431 Volts per Tesla, while the range of sensitivity of the electronics sensor is 0.154 to 242.28 Volts per Tesla. Fig. 5 and Fig.6 show the smallest, the average, and the largest sensitivity values of both electronics and spintronics current sensors using line graph, and bar graph respectively. From both graphs we can observe that, the sensitivity of spintronics current sensors is in a very low range than electronics current sensor. For further clarification, Fig. 7 presents the comparison of the smallest sensitivity values of both spintronics and electronics current sensor in the form of bar graph.

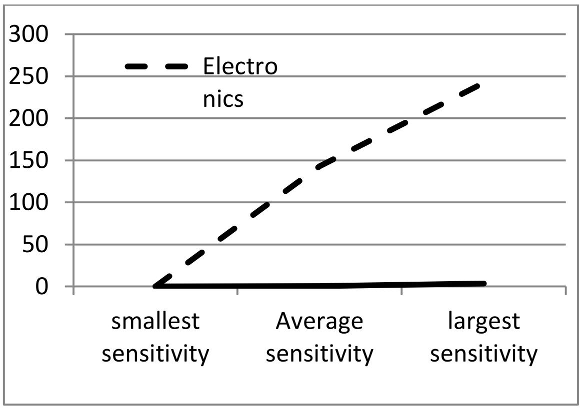

Fig. 5. Smallest, Largest and Average sensitivity of spintronics Vs Electronics current sensor in line graph

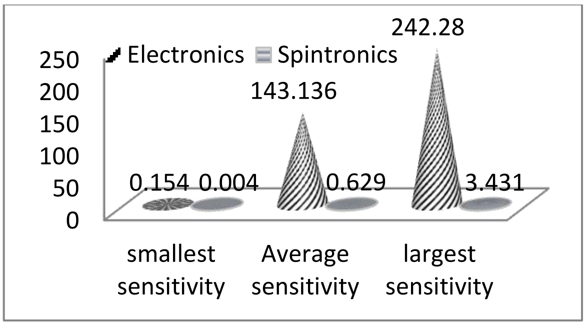

Fig. 6. Smallest, Largest and Average sensitivity of spintronics Vs Electronics current sensor in bar graph

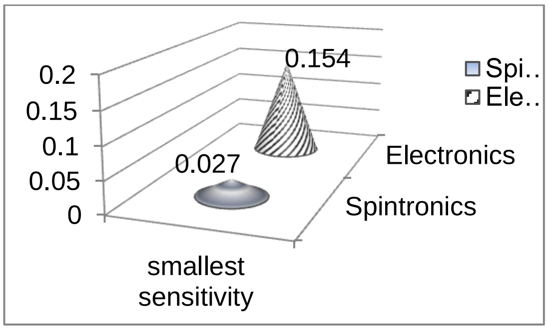

Fig. 7. The Smallest sensitivity of spintronics Vs Electronics current sensor in bar graph

CONCLUSION

In this paper, the working principle of spintronics devises in relation to the conventional electronics devises is discussed. Survey of research works on electronic sensors with different configurations is made and also survey of researches on spintronics based sensors with different configuration is done each separately.

Based on the sensitivity parameter of the sensors, the researches done by the two different schools is investigated and compared. The results of comparison are demonstrated by tables and graphs. Based on the survey we did, and from the comparison results we observed we conclude that the spintronics current sensors are highly sensitive and more applicable than the conventional electronics current sensors.

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