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A Novel Approach based on Combination of Spintronics and Quantum Thermodynamics to produce Ambient Energy at Room Temperature

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Abstract

A Novel Approach based on Combination of Spintrinics and Quantum Thermodynamics to produce Ambient Energy has been suggested. The suitability of various materials for designing and fabricating Spin Engine based on Spintronics and Quantum Thermodynamics has been technically discussed. The designing aspects of the Anomalous Nersnt Effect (ANE), play an important role in this technique. The paper is expected to be useful for the designers and engineers engagd in this novel evolving field.
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Keywords: Ambient Energy at Room Temperature, Spintronics, Quantum Thermodynamics, Anomalou Nersnt Effect, and Spin Engine.

Resumen

Se ha sugerido un enfoque novedoso basado en la combinación de espintrínica y termodinámica cuántica para producir energía ambiental. Se ha discutido técnicamente la idoneidad de varios materiales para diseñar y fabricar Spin Engine basado en Spintronics y Termodinámica Cuántica. Los aspectos de diseño del Efecto Nersnt Anómalo (ANE), juegan un papel importante en esta técnica. Se espera que el documento sea útil para los diseñadores e ingenieros involucrados en este novedoso campo en evolución.

Palabras clave: Energía ambiental a temperatura ambiente, Espintrónica, Termodinámica cuántica, Efecto Nersnt Anómalo y Motor de giro.

I. INTRODUCTION

In modern age, there is quite a shortage of usable energy, and the scientists and engineers are struggling with huge efforts for mitigating the ill-effects of man-made climate changes, and taking various adaptation steps. It has now been understood and realized that the prevailing fossil fuel-free technologies are not sufficient to meet this difficult challenge. In this direction, a new technological approach based on novel Physics concepts has been tried. A group of Scientists from international scientific organizations from the CNRS, the University of Strasbourg, and University of Lorraine in France, have joined hands with the Uppsala University in Sweden, and have been able to discover a complex concept based on two different research topics: (i) Spintronics, which is now being considered as the next-generation, low-power electronics [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11] , utilizing the quantum spin property of the electrons, which mainly deals with information storage; and (ii) Quantum thermodynamics, considering the matter to be confined at the nanoscale to exhibit quantum properties, thereby understanding the operation of quantum engines. Their experimentation and theoretical analysis have led to explain the possibility of assembling an electrical generator based on utilizing the electron spin for harvesting thermal fluctuations at room temperature.

II. THE WORKING PRINCIPLE

The harvesting of ambient temperature takes place over paramagnetic (PM) centers, which are atom-level magnets, whose orientation fluctuates due to heat. The electrodes of the engine, called spintronic selectors, allow electrons of only one spin! (up↑) or (down↓) to conduct.

A. Process

Since heat mixes the electron spin on the PM center with energetically separated spin energy levels, the transport between the PM center and the electrodes occurs at different energy levels for each electrode, which causes a spontaneous bias voltage V to appear between the electrodes, and thus resulting in a spontaneous current to flow after the electrical circuit is closed.

The group of Scientists, as stated above, has succeeded in establishing a link between this spin engine concept and room-temperature experiments on a solid-state spintronic device called a magnetic tunnel junction (MTJ), by applying analytical and ab-initio theories.

Generally, the interface between the ferromagnetic metal Co and carbon atoms is used as a spintronic selector, and carbon atoms substitute oxygen atoms in the MgO tunnel barrier to act as PM centers.

It is being emphasized on the basis of the experiments that the concept of MTJs within next-generation memories, could lead to the development of chips capable of continuously producing electrical power with an areal power density, which is three times greater than the raw solar irradiation on Earth.

B. Designing aspects of spintronic devices

The main parameters for designing the Spintronic devices, are Magnetoresistance, Magneto Tunneling Junction (MTJ), and Tunneling Magnetoresistance (TMR).

These have to be chosen and optimized differently for each spintronic device under consideration. The difference in the theoretical value and the achieved value, has to be corrected by applying the feedback from the achieved value, which needs the experience and expertise of the designer, who has to do a number of iterations with the help of software.

The MTJ in its simplest form, consists of an insulator sand witched between two feromagnets; one in parallel and the other in antiparallel configuration. The Tunneling Magnetoresistance (TMR) is given by:

$$\mathrm{TMR} = [\frac{(R_{ap} = R_p)}{R_p}], \qquad (1)$$

where R_{ap} and R_p are redpectively the resistance for the antiparallel configuration, and the parallel configuration. Hence, the different options before the designer for increasing the TMR are: (i) by increasing the difference between R_{ap} and R_p, and (ii) by minimizing R_p.

The Magnetoresistance (MR) depends strongly on the applied field, which clearly is low/high when the polarization of the magnetic layers is parallel/antiparallel. Thus, it is clear that TMR can be optimized, by selecting the proper electric field, and also considering the values of R_{ap} and R_p.

The designing of the Spintronic devices can be done efficiently by Yu and Flatte‘s Model, which assumes a bias-independent spin polarization at the interface, and is based on the introduction of a drift term in the equation describing spin injection:

$$\nabla^2 (n_{up} - n_{down}) + \frac{eE}{k_B T \nabla^2 (n_{up} - n_{down})} = \frac{(n_{up} - n_{down})}{L^2(s)}, \qquad (2)$$

where nup and ndown give respectively the numbers (in fractions) of electrons with upward spin and downward spin, e is the electron charge, E is the electric field, k_B is the Boltzman constant, and $L(s)$ is spin diffusion length. Interestingly, Drift term, at quite high fields causes: (i) Very large spin diffusion lengths in the NMS, so that effectively a = *b*, and (ii) A change in the conductivity of the spin-channels in the bulk of the NMS due to repopulation effects.

By following theTwo current model, the total device resistance (TDR) is given by:

$$\mathrm{TDR} = (\mathrm{RFM} + 2\mathrm{RSC}) \sim 2\mathrm{RSC}\ , \qquad (3)$$

where RFM and RSC are respectively the ferromagnet resistance and semiconductor resistance.

In addition, the current is determined only by semiconductor.

$$\frac{\Delta R}{R_{parallel}} = [\frac{\beta^2}{(1-\beta^2)}][\frac{\mathrm{RFM}^2}{\mathrm{RSC}^2}][\frac{4}{(2\frac{\mathrm{RFM}}{\mathrm{RSC}}+1)^2 - \beta^2}], \qquad (4)$$

where ΔR is the difference in the resistance values in the two states (parallel and anti parallel), and *Rp* is the resistance for the parallel state. The designer has to optimize the value of TMR by properly choosing ΔR, RFM, RSC, and $R_{parallel}$.

III. DESIGNING ASPECTS OF SPIN ENGINE

The designers have to confirm some fundamental design aspects of the operation of Spin Engine, and also achieve it's reproducibility by controlling at the atomic level, both the position and properties of the PM centers in a suitable solid-state device, for implementing CMOS back-end integration for managing various engineering issues including heat flow and interconnect losses. In addition, they have to choose the materials for minimizing the climate effect.

Ambient power, or energy scavenging, is the process of deriving energy from external sources, like solar power, and wind energy, captured and stored for small, autonomous devices, like those used in wearable electronics. There are many types of energy generation [12, 13, 14, 15, 16] like from wind, water, and fossil etc. However, Spintronics and

Quantum thermodynamics, provide a novel approach of production of ambient power.

Another approach is that of the semi classical model of charge and spin transport based on the drift–diffusion theory, in which we consider transport in metallic/semiconducting nonmagnets and metallic ferromagnets, by limiting the diffusion and designing to diffusive dynamics, and assuming that the density and external fields are slowly varying on the scale of the mean free path λ, which is considered to be smaller than the spin diffusion length LSD, Also, as the transport description is semiclassical, the quantum tunneling and interference are neglected. This approach is based on the assumptions: (i) slow spin relaxation processes to establish correct equilibrium polarization; (ii) weak external fields to ensure the working to be within the linear response theory; (iii) absence of spin Hall effect, and spin Coulomb drag; and (iv) no presence of space charge effects. For this approach, it is convenient to consider the structure as shown in Fig. 1, which consists of a ferromagnet (F) in contact with a nonmagnet (N).

It can be seen that the F/N bilayer is under the effect of an electric field governed by (i)a charge voltage V_C, and (ii) a magnetic field: $B=\mu_0 H$, where μ_0 is the permeability of vacuum and H is the magnetic field intensity). Here, the ferromagnet is assumed to have in-plane magnetic anisotropy. However, the following results and analysis thereafter generally hold for ferromagnets with perpendicular magnetic anisotropy.

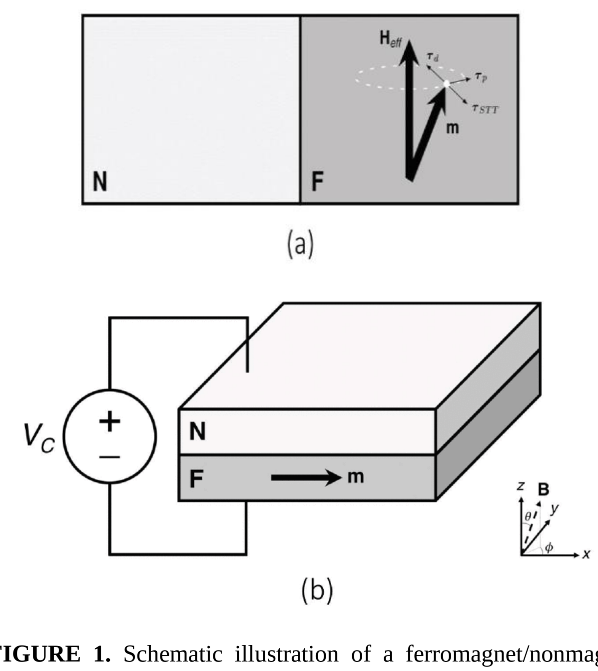

FIGURE 1. Schematic illustration of a ferromagnet/nonmagnet (F/N) bilayer. (a) 2-D view showing the rescale magnetization m, the effective magnetic field Heff, and the acting torques. (intrinsic damping τd, precession τ_p, and STT τST T [17]). (b) 3-D view showing the external fields: 1) an electric field E governed by a charge voltage V_C and 2) an arbitrarily oriented magnetic field B of magnitude B and orientation angles φ and θ. Using the spin or Boltzmann equation, a set of flux equations can be derived for the four macroscopic quantities, which are: charge density n(r, t) spin density s(r,t), charge current density JC(r, t), and spin current density JS(r, t), where r and t are space and time variables; and spin density is defined as the total electron density of electrons of one spin minus the total electron density of the electrons of the other spin. The designer has to optimize these quantities for obtaining the maximum flux. For simplifying the treatment,1-D transport along the z -axis in a nonmagnet is considered, within a relaxation time approximation.

The materials for fabricating devices based on Spintronics and Quantum thermodynamics have to be chosen separately for the two. There are about 50 Energy materials, 100 Metallic materials, and 200 Magnetic materials. The anomalous Nernst effect (ANE), one of the thermomagnetic effects studied by many researchers in various fields, has recently drawn the attention of the scientific community engaged in the Spitronics based devices, especially from the point of view of ambient power generation.

It is really interesting to note that the ANE, which is produced from the fictitious fields in momentum space, has been able to understand the intersction among three different concepts of heating, spin, and charge in magnets. Also, contrary to the Seebeck effect, it has many advantages for application for highly efficiency energy-harvesting devices, since it can provide simpler lateral structure, higher flexibility, and most importantly, much lower production cost.

The designer has to choose the method for modulating the ANE for its thermoelectric applications, and also to design materials for obtaining large ANE including Weyl magnets, and thermoelectric devices for efficiently using the ANE.

In the last decade, the research field covering spintronics and thermoelectrics, termed 'spin caloritronics', has drawn the attention of various researchers [16].

The advantage in case of thermoelectric conversion from heat to electric energy by using spin is that spin can be controlled easily by a small energy in the nanostructures, which has led to the development of the energy-harvesting technology. Here it is to be noted that though the Seebeck effect, as thermoelectric effect is widely used in many nonmagnetic thermoelectric devices, because it directly converts heat into electricity; which can be created along the direction of temperature gradient, yet the Nernst effect, another well-known thermoelectric effect [17, 18)], has been found to be useful for energy harvesting. More novel Studies on this evolving topic [19, 20] have recently been reported.

A. Theory

From the laws of Electromagnetism, we know that when the temperature gradient (dT/dx) and the magnetic field (H), both normal to each other, are applied to a conductor, an electromotive force is induced perpendicular to both (dT/dx) and H, which gives rise to a Nernst voltage.If we consider a case, if the material has a spontaneous magnetization, spontaneous term of the Nernst effect becomes superimposed on the normal Nernst term; and this spontaneous term is called the anomalous Nernst effect (ANE) and frequently observed in ferromagnetic materials.

Since, the normal Nernst effect is proportional to magnetic field *B*, therefore, enough magnetic field is required for the thermoelectric conversion. However, to the contrary, the ANE is spontaneous at zero field, and proportional to saturation magnetization in principle. It has been established by the recent experimental and theoretical studies, that it originates from the fictitious field in the momentum space in magnets and can be particularly enhanced when the Weyl points are tuned to be close to the Fermi energy. Hence, the designer has to ensure the magnetic materials with large *Q* s and/or *M* s are developed, and also, the remanence state is used, then ANE occurs even without applying a magnetic field. It is this unique feature of the ANE, which makes it suitable for the thermoelectric conversion process. However, it is still a challenge to develope actual devices based on the Nernst effect, or the ANE. It has been claimed that large ANE is observed in an antiferromagnetic bulk with a very small magnetization. The Nernst effect is a thermoelectric , or a thermomagnetic phenomenon, which is observed when a sample allowing electrical conduction is subjected to a magnetic field and a temperature gradient normal to each other, and thus , an electric field is induced normal to both. This effect is quantified in terms of the Nernst coefficient |*N*|, which is defined as:

$$|N| = \{\frac{(E_Y / B_Z)}{(dT / dx)}\}, \qquad (6)$$

where E_Y is the *y*-component of the electric field resultng from the magnetic field's z-component B_Z, and the temperature gradient (*dT/dx*). Thus, the designer has to optimize the increase in E_Y, decrease in B_Z, and also minimizing the derivative (*dT/dx*), *i.e*. the rate of change of temperature with distance.

IV ADVANTAGES OF ANE-BASED ENERGY-HARVESTING THERMOELECTRIC CONVERSION SYSTEM

A very important advantage of the Nernst effect is that the observed Nernst voltage is not governed by the temperature difference, but by the temperature gradient. Though, in case the Seebeck effect also, the voltage increase is proportional to the temperature gradient, the problem is that, a sufficient length of the material along the temperature gradient is needed for achieving a large temperature difference, which decides the Seebeck voltage. However, in case of the Nernst effect, if the temperature gradient is provided, not much length of the material along the temperature gradient is required, since the Nernst voltage increases with the transverse length normal to both the temperature gradient and the magnetic field. Hence, the Nernst effect has been established as suitable for the thermoelectric conversion system consisting of thin materials, and as a result is useful to design a flexible device to fit any type of curved surface of a heat source.

Recent experiments have shown that the spin Seebeck effect has been found innovating from thermoelectric applications point of view. However, a spin detection material with a strong spin-orbit interaction (SOI) such as Pt is required for the spin Seebeck effect, as the thermally generated spin current is converted to voltage in the material.

V CONCLUDING REMARKS

In modern times of the tremendous increase in the requirement of Energy, a new method of the Ambient Powed based on Spinttonics and Thetmodynamics seems to have a good potential. The recent spurt in the studies of Spintronics, and Nersnt Effect, seems to be having a lot of potential. The works on the individual technologies of Spintronics, Renewal Energy, and Anomalous Nersnt Effect, have been very successful. Still, the combined Technology based on all three is a quite daunting task. The designer has to choose such materials which satisfy all three basic technologies, and also to optimize variou Parameters to achieve maximum output from each of them. This is quite complicated, and may require the experience and expertise of the designer, and also access to computer softwares. To conclude, making this technology really useful, more concerted efforts have to be made.

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REFERENCES

[1] Chopra, K. N., *A Technical Note on Spintronics (An Off -shoot of Electronics) – its Concept, Growth and Applications*, Atti Fond G. Ronchi **68**, 293-303 (2013).

[2] Chopra, K. N., *A Short Note on the Organic Semiconductors and their Technical Applications in Spintronics*, Lat Am J Phys Educ. **7**, 674-679 (2013).

[3] Chopra, K. N., *New Materials and their Selection for Designing and Fabricating the Spintronic Devices – A Technical Note*, Atti Fond G. Ronchi **68**, 673-680 (2013).

[4] Li X. X., Wu X. J., and Yang J. L. *Control of spin in a La(Mn,Zn)AsO alloy by carrier doping*, J Mater Chem. **C 1,** 7197201 (2013).

[5] Zhang J. H., Li, X. X. and Yang, J. L., *Electrical control of carriers' spin orientation in the FeVTiSi Heusler alloy*, J Mater Chem **C 3**, 25637 (2015).

[6] Chopra, K. N., *A Short Note on Ferromagnetism by Doping, and its Applications to "Spintronics*", Atti Fond G. Ronchi **69**, 27-38 (2014).

[7] Chopra, K. N., *Mathematical Aspects of Spin-related Phenomena Models and the Associated Criteria for Spintronics*, Lat Am J Phys E **8**, 4313-1 - 4313-6 (2014).

[8] Chopra, K. N., *A Short Review on Designing and Fabrication of Spintronic Devices*, Atti Fond G. Ronchi **69** 223-234 (2014).

[9] Hals, K. M. D., Tserkovnyak, Y., and Brataas, A., *Phenomenology of current-induced dynamics in antiferromagnets*, Phys Rev Lett. **106**, 107206 (2011).

[10] Gomonay, H. and Lokte, V., *Hydrodynamic theory of coupled current and magnetization dynamics in spin-textured antiferromagnets*, (2013) arXiv:1305.6734.

[11] Gomonay, E. V. and Loktev V.M., *Spintronics of antiferromagnetic systems (Review Article*) Low Temp Phys. **40**, 1735 (2014).

[12] Chopra, K. N., *Optimization of the Conversion of the Geothermal Energy into Electricity – A Short Note*, Atti Fond. G. Ronchi **70**, 17-25 (2015).

[13] Chopra, K. N., *Biophotonics and Optofluidics Technology –Technical Analysis and Qualitative Review of the Novel Applications*, Lat Am J Phys Educ. **8**, 533-540 (2014).

[14] Chopra, K. N., *Technical Analysis of the Maximization of the Thermo-Chemical Solar Power with special reference to Fulvalene Diruthenium,* Atti Fond. G. Ronchi **71**, 213-220 (2015).

[15] Chopra, K. N., *Technical Treatment of the Efficiency Maximization of the Highly Efficient Oxygen-producing Electrodes for Splitting Water Technology*, Atti Fond. G. Ronchi **71**, 579-587 (2016).

[16] Bauer, G. E., Saitoh, E. and Wees, B. J. Van *Spin Caloritronics*, Nat Mater. **11**, 391 (2012).

[17] Himanshu, S., Zhenchao, W., Koki, T. and Masaki, M., *Anomaly in anomalous Nernst effect at low temperature for C1b-type NiMnSb half-Heusler alloy thin film*, Jpn J Appl Phys. **58**, SBBI03 (2019).

[18] Hasegawa1, K., Mizuguchi, M., Sakuraba, Y., Kamada, T., Kojima, T., Kubota, T., Mizukami, S., Miyazaki, T. and Takanashi, K., *Material dependence of anomalous Nernst effect in perpendicularly magnetized ordered-alloy thin films*, Appl. Phys. Lett. **106**, 252405 (2015); https://doi.org/10.1063/1.4922901

[19] Bose, A. and Tulapurkar, A., *Recent advances in the spin Nernst effect*, Magnetic Materials **49**, 165526 (2019).

[20] Mizuguchi, M. and Nakatsuj, S., *Energy-harvesting materials based on the anomalous Nernst effect*, Science and Technology of Advanced Materials **20**, 262-275 (2018).