Hindawi Publishing Corporation
Research Letters in Physics
Volume 2008, Article ID 434936, 4 pages
doi:10.1155/2008/434936

Research Letter

Light Emitting Diodes of Inverse Spin Valves

X. R. Wang

Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong

Correspondence should be addressed to X. R. Wang, phxwan@ust.hk

Received 15 May 2008; Accepted 8 July 2008

Recommended by Yuan Feng

Light emitting diodes made out of inverse spin valves of a ferromagnetic half metal sandwiched between two nonmagnetic metals are proposed. Based on a giant spin-dependent chemical potential difference created under an external bias, the inverse spin valves are possible to emit light when electrons with the higher chemical potential flip their spins and become the electrons of the opposite spin with the lower chemical potential. The frequency of this type of light emitting diodes is tunable by the bias.

Most light emitting diodes (LEDs) are made of either nonmagnetic semiconductors or organic semiconductors. The working principle of an LED is to create a situation where electrons occupy higher energy levels and some of the lower energy levels are unoccupied so that electrons can move to those lower energy levels by emitting photons. One of the popular ways to achieve this in the conventional LEDs is through a p-n junction where electrons are injected into the conduction band on one side and holes into the valence band on the other side (of the junction) when the LED is electrically biased in the forward direction of the junction. As long as an electron and a hole are spatially not too far apart, they can radiatively recombine and emit incoherent narrow-spectrum light. Thus, the emitted light depends largely on the energy difference between electrons and holes. This is also why a proper electronic structure is normally required for LED materials. How much the light frequency is tunable depends on the detail energy band structure of the LED material. On the other hand, all materials can emit light if they are in excited states. The question that we would like to ask is whether it is possible to make an LED out of materials that are normally not for LEDs. In this letter, we propose an inverse spin valve device in which the chemical potentials of spin-up (SU) and spin-down (SD) electrons split when an external bias is applied. The degree of the split is at the magnitude of applied bias, and is due to the spin-dependent electron transport. Thus the device can emit tunable light under an external bias. Interestingly enough, this inverse spin valve is made out of both nonmagnetic and magnetic metals. Traditionally, one will not relate LEDs with magnetism where one may be interested in the magnetization reversal [1–6]. Furthermore, the emitted light is not sensitive to the particular materials used, and thus it is an LED out of any material.

A conventional spin valve is a layered structure of a nonmagnetic spacer sandwiched between two ferromagnetic metals. An inverse spin valve is a layered structure with a ferromagnet sandwiched between two nonmagnetic metals. As illustrated in Figure 1(a), $M1$ and $M2$ are two nonmagnetic metals. To maximize the spin-related chemical potential split, the ferromagnetic spacer is chosen to be a half metal (HM) that acts as a conductor to electrons of one spin orientation (spin-up), but as an insulator to those of the opposite orientation (spin-down). Then only SU electrons can pass through the half metal when an external bias is applied on the inverse spin valve. SD electrons will be blockaded from the flow through the spacer. Similar to a giant magnetoresistance [7–9] or tunneling magnetoresistance [10, 11] device, electron transport of an inverse spin valve is spin-dependent.

The spin-dependent electron transport of an inverse spin valve leads to spin-dependent Fermi levels in nonmagnetic metals near the nonmagnetic-magnetic interfaces under a bias. Consider one inverse spin valve connected to a battery of voltage V. Let us assume that the electron chemical potential in $M1$ is initially moved up by eV while that of $M2$ is kept unchanged [12]. The electron flow diagram is shown in Figure 1(b). $M1$ and $M2$ each has two electron reservoirs. One is for SU electrons, and the other is for SD electrons (denoted by rectangular boxes). SU electrons in $M1$ can flow into the empty SU electronic states in $M2$ via

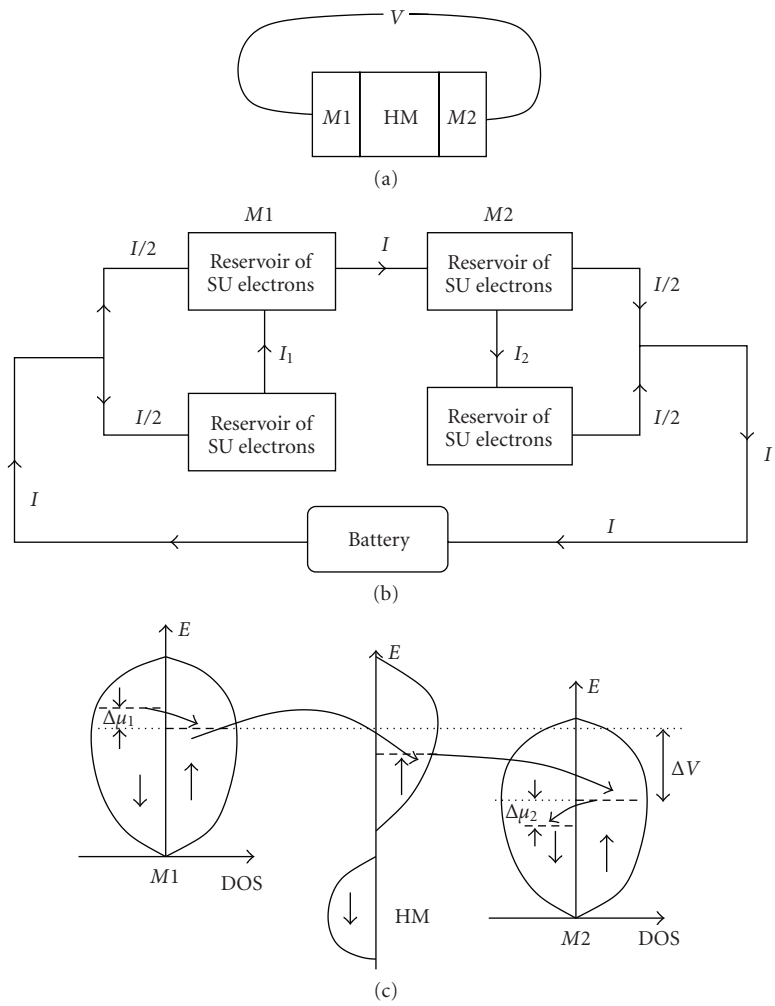

Figure 1: (a) Schematic illustration of the inverse spin valve. $M1$ and $M2$ are nonmagnetic metals. HM is a ferromagnetic half metal. V is the applied bias. (b) Electron flow from and into spin-up and spin-down states in $M1$ and $M2$. In the steady state, current flowing into any reservoir should be equal to those flowing out. (c) Relative chemical potentials of spin-up and spin-down electrons in nonmagnetic metals and half metal. The curved arrows indicate the electron flow. Dash lines indicate the chemical potential levels of spin-up and spin-down electrons in half metal and nonmagnetic metals. $\Delta\mu_1$ and $\Delta\mu_2$ are the chemical potential splits between spin-up and spin-down electrons at the left and right nonmagnetic-magnetic interfaces. ΔV is the effective bias on the half metal.

the empty SU electronic states in the half metal, generating a current I from $M1$ to $M2$. There is no current between the SD-electron reservoir of $M1$ and SD-electron reservoir of $M2$ due to the spin blockade of the half metal. The same amount of electrons will be pumped back from $M2$ to $M1$ by the battery to keep the electron neutrality in $M1$ and $M2$. However, a battery does not distinguish electron spin, and it pumps equal amounts of SU and SD electrons. In other words, SU electrons flow out of $M1$ and into $M2$. In the meanwhile, an equal amount of electrons with half of them in the SU state and the other half in the SD state are drawn out of $M2$ and are supplied into $M1$ by a battery. As a result, $M1$ accumulates more SD electrons, and $M2$ accumulates more SU electrons. Thus, the chemical potential of the SD electrons is higher than that of the SU electrons in $M1$. Vice versa, the Fermi level of SU electrons is higher than that of SD electrons in $M2$. Figure 1(c) is an illustration of the Fermi levels (denoted by the dash lines) of SU and SD electrons in nonmagnetic metals and half metal. The electron density of states (DOSs) in the figure for nonmagnetic metals and half metal is just a sketch. $\Delta\mu_1$ and $\Delta\mu_2$ are the chemical potential differences between SU and SD electrons in $M1$ and $M2$, respectively. ΔV is the chemical potential difference between the SU electrons in $M1$ and the SU electrons in $M2$.

SD electrons in $M1$ can only go to $M2$ by first flipping their spins and changing to SU electrons. The only supply of the SD electrons to $M2$ is from the conversion of the SU electrons in $M2$ through spin flipping. As shown in Figure 1(b), these lead to the internal currents I_1 (I_2) in $M1$ ($M2$) between SD-electron and SU-electron reservoirs. Assume the spin flip occurs only near nonmagnetic-magnetic interfaces within a width of spin diffusion length ξ_1 (ξ_2) in $M1$ ($M2$). This is justified because ξ_i ($i = 1, 2$) is the length scale over which a chemical potential difference can maintain, and the conversion rate of SU and SD electrons from each other is the same when both SU and SD electrons have

the same Fermi levels (chemical potentials). Let τ_1 (τ_2) be the spin flipping time (spin-relaxation time T_1 [13]) in $M1$ ($M2$), corresponding to the flipping rate of $1/\tau_1$ ($1/\tau_2$). The conversion rate from the SD (SU) electrons to the SU (SD) electrons in $M1$ ($M2$) is the product of the excess SD (SU) electrons $n_1\Delta\mu_1\xi_1 A$ ($n_2\Delta\mu_2\xi_1 A$) and the single electron flipping rate. Thus I_i ($i = 1, 2$) is

$$I_i = \frac{n_i \Delta\mu_i e \xi_i A}{\tau_i}, \tag{1}$$

where n_1 (n_2) is the density of states of the SD electrons in $M1$ ($M2$) at the Fermi level. A is the cross-section areas.Neglecting the tunneling by the SD electrons through the half metal and assuming a resistance R for the SU electrons, the current I from$M1$ to$M2$ is

$$I = \frac{\Delta V}{R}. \tag{2}$$

In the steady state, there is no net electron build up anywhere in the circuit. Since the current through the battery is unpolarized, half of the current is made up by the SU electrons and the other half is from the SD electrons. Balance conditions and external constraint require

$$\begin{aligned} I_1 = I_2 &= \frac{I}{2}, \\ \frac{\Delta\mu_1}{e} + \frac{\Delta\mu_2}{e} + \Delta V &= V. \end{aligned} \tag{3}$$

Solving (1)–(3), the spin-dependent chemical potential differences $\Delta\mu_1$ and $\Delta\mu_2$ are

$$\begin{aligned} \Delta\mu_1 &= \frac{(eV)\tau_1/(n_1 e^2 \xi_1 A)}{2R + \tau_1/(n_1 e^2 \xi_1 A) + \tau_2/(n_2 e^2 \xi_2 A)}, \\ \Delta\mu_2 &= \frac{(eV)\tau_2/(n_2 e^2 \xi_2 A)}{2R + \tau_1/(n_1 e^2 \xi_1 A) + \tau_2/(n_2 e^2 \xi_2 A)}. \end{aligned} \tag{4}$$

It is interesting to see that the largest chemical potential splits occur at $R = 0$, a short circuit for SU electrons! The chemical potential splits are largely determined by the applied bias. Thus they could be the order of eV if the steady current (controlled by the relaxation time and bias) is not too large to cause an electric breakdown. The half metal may also be replaced by an ordinary ferromagnet. In this case, SD electrons in $M1$ can also flow directly into $M2$. As long as there is a spin-dependent electron transportation, the spin-related chemical potential differences in $M1$ and $M2$ always exist but their values will be reduced by a factor of $(1 - R/R')$, where R' is the resistance of the ferromagnet for the SD electrons (minority carriers).

Results of (4) mean the population inversion of the electrons in the electrically biased inverse spin valves. As shown in Figure 2(a) for $M1$, SU electronic states below their Fermi level are fully occupied (at zero temperature) while the SD electronic states in the energy range of $\Delta\mu_1$ between SU electron Fermi level and SD electron Fermi level are empty. Thus an SU electron can go to a lower empty SD electronic state and emit a photon. One can then apply standard theory of LED to the inverse spin valve device to make an LED or even a laser by incorporating the device with a cavity [14]. However, unlike the usual light source

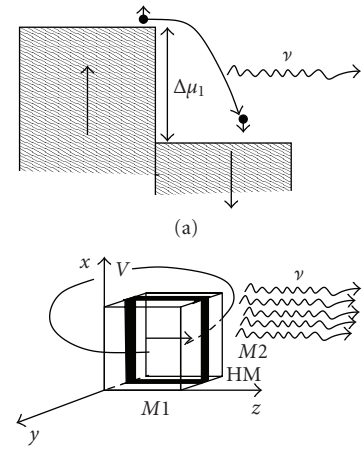

Figure 2: (a) Schematic illustration of light emitting process in $M1$. SU electrons near the Fermi level jump to the lower empty SD electronic states, and emit photons of well-defined polarity. (b) A sketch of a possible LED out of an inverse spin valve. If the magnetization of the half metal is along the z-axis, the light emitted by $M1$ along the $+z$-direction will be right-hand circularly polarized. No light will emit in the xy-plane.

of atoms and semiconductors where spin does not involve in the electron transitions, the light source here is spin resolved. For example, in the case that the magnetization of the half metal is along the $+z$-direction, the spin-up ($+z$-direction) electrons in $M1$ are in higher energy levels, and they can only go to spin-down states. Due to the angular momentum conservation, the spin of the emitted photon must be along the $+z$-direction. In other words, the light out of an inverse spin valve is polarized. Its polarization depends on the light propagation direction and magnetization of the half metal. As shown in Figure 2(b), the light emitted in the $+z$-direction is right-hand circularly polarized light, and left-hand circularly polarized light in the $-z$-direction. Because of the two-component nature of photons (angular momentums must be parallel to light propagation direction), no light can emit in the direction perpendicular to the magnetization of the half metal (xy-plane).

It should be clear that electroluminescence in a spin-flip transition does not violate any fundamental principles, such as energy, angular momentum, and linear momentum conservations. The energy and angular momentum conservations are satisfied by emitting a photon with a proper frequency and angular momentum. Linear momentum conservation is easily satisfied, just as all radiative transitions in vapors or liquids or solids that can absorb readily any negligible linear momentum of a photon (this is why a good optical semiconductor should have a direct band gap). In a normal LED, radiative transitions occur between two states in two different bands with opposite parities. To have a finite dipole-induced electroluminescence, one needs a nonzero dipole matrix element $\langle\beta|\vec{x}|\alpha\rangle \neq 0$, where $|\alpha\rangle$ and $|\beta\rangle$ are the initial and finite electronic states (in the same band). Thus, this is only possible in a metal without inversion symmetry! This requirement is similar to that in a cascade laser [15] of

superlattices. Electroluminescence in a spin-flip transition is also supported by the fact that magnetization dynamics can be manipulated by the laser of femtosecond time-scales [16]. This fact indicates a strong coupling between photons and electron spin-flipping. Furthermore, in a conventional semiconductor, an electron decay within the same energy band is dominated by nonradiative one due to the electron-photon interaction whose time scale is typically picoseconds in comparison with nanoseconds for a radiative one. The nonradiative decay is expected to be greatly suppressed in our system because the direct photon-electron and electron-electron interactions cannot flip electron spins. Thus, radiative decay from occupied SU electron states to empty SD electron states should be the favored channel. Of course, nonradiative decay is still possible when the spin-orbital coupling is strong.

In comparison with the usual semiconductor LEDs, there are a few nice features about the proposed LED. (1) Photons have a well-defined polarization because both occupied and unoccupied states have well defined spins. (2) The population inversion is not very sensitive to the detail electronic structure, thus the physics is very robust, and one can in principle use any conducting materials, magnetic or nonmagnetic and organic or inorganic, to make LEDs. (3) The spin-dependent chemical potential difference is controlled by an external bias, thus the light frequency can be electrically tuned over very broad range.

Zero temperature is assumed in (1). For a finite temperature, electron distribution is no longer described by a step-function, and (1) should be modified. Also, the spatial variation of the Fermi level is neglected in the present work. In principle, Fermi levels of both SU and SD electrons vary in space because of electron diffusion, spatial distribution of electrons, and spin flipping. The spatial variation of the Fermi levels may also modify (1). For practical applications, it is interesting to work out a more careful analysis by taking into account the electron distribution in both energy and space although one should not anticipate any change in physics.

The working principle of currently proposed LED device is different from the traditional ones. Unlike many previous LEDs where electron spin degrees of freedom were not used, the LED devices here are largely based on manipulating electron spins through the spin-dependent electron transport in inverse spin valves so that it is possible to create higher occupied SU (SD) electron levels and lower unoccupied SD (SU) levels. The population inversion does not occur between states of the same spin, but for opposite spin instead. However, it should be pointed out that concept of spin-LED is not new [17, 18].

In conclusion, we propose a very robust LED device made of almost any material. Unlike the usual LEDs that rely on detail energy spectrum of the material, the proposed technology uses electron spin blockage to create a population inversion of electrons.

ACKNOWLEDGMENTS

The author would like to thank Professor Yongli Gao and Professor John Xiao for the useful discussions. This work is supported by Grants no. RPC07/08.SC03, RGC/GRF603508, RGC/CERG603007, and SBI07/08.SC09.

REFERENCES

[1] X. R. Wang and Z. Z. Sun, "Theoretical limit in the magnetization reversal of Stoner particles," *Physical Review Letters*, vol. 98, no. 7, Article ID 077201, 4 pages, 2007.

[2] Z. Z. Sun and X. R. Wang, "Theoretical limit of the minimal magnetization switching field and the optimal field pulse for Stoner particles," *Physical Review Letters*, vol. 97, no. 7, Article ID 077205, 4 pages, 2006.

[3] Z. Z. Sun and X. R. Wang, "Fast magnetization switching of Stoner particles: a nonlinear dynamics picture," *Physical Review B*, vol. 71, no. 17, Article ID 174430, 9 pages, 2005.

[4] Z. Z. Sun and X. R. Wang, "Strategy to reduce minimal magnetization switching field for Stoner particles," *Physical Review B*, vol. 73, no. 9, Article ID 092416, 4 pages, 2006.

[5] Z. Z. Sun and X. R. Wang, "Magnetization reversal through synchronization with a microwave," *Physical Review B*, vol. 74, no. 13, Article ID 132401, 4 pages, 2006.

[6] T. Moriyama, R. Cao, J. Q. Xiao, et al., "Microwave-assisted magnetization switching of $Ni_{80}Fe_{20}$ in magnetic tunnel junctions," *Applied Physics Letters*, vol. 90, no. 15, Article ID 152503, 3 pages, 2007.

[7] M. N. Baibich, J. M. Broto, A. Fert, et al., "Giant magnetoresistance of (001)Fe/(001)Cr magnetic superlattices," *Physical Review Letters*, vol. 61, no. 21, pp. 2472–2475, 1988.

[8] G. Binach, P. Grünberg, F. Saurenbach, and W. Zinn, "Enhanced magnetoresistance in layered magnetic structures with antiferromagnetic interlayer exchange," *Physical Review B*, vol. 39, no. 7, pp. 4828–4830, 1989.

[9] R. F. C. Farrow, C. H. Lee, and S. S. P. Parkin, "Magnetic multilayer structures," *IBM Journal of Research and Development*, vol. 34, no. 6, pp. 903–915, 1990.

[10] T. Miyazaki and N. Tezuka, "Giant magnetic tunneling effect in $Fe/Al_2O_3/Fe$ junction," *Journal of Magnetism and Magnetic Materials*, vol. 139, no. 3, pp. L231–L234, 1995.

[11] J. S. Moodera, L. R. Kinder, T. M. Wong, and R. Meservey, "Large magnetoresistance at room temperature in ferromagnetic thin film tunnel junctions," *Physical Review Letters*, vol. 74, no. 16, pp. 3273–3276, 1995.

[12] S. D. Wang, Z. Z. Sun, N. Cue, H. Q. Xu, and X. R. Wang, "Negative differential capacitance of quantum dots," *Physical Review B*, vol. 65, no. 12, Article ID 125307, 4 pages, 2002.

[13] X. R. Wang, Y. S. Zheng, and S. Yin, "Spin relaxation and decoherence of two-level systems," *Physical Review B*, vol. 72, no. 12, Article ID 121303, 4 pages, 2005.

[14] H. Haken, *Laser Theory*, Springer, New York, NY, USA, 1983.

[15] F. Capasso, *Physics of Quantum Electron Devices*, Springer, New York, NY, USA, 1990.

[16] A. V. Kimel, A. Kirilyuk, P. A. Usachev, R. V. Pisarev, A. M. Balbashov, and Th. Rasing, "Ultrafast non-thermal control of magnetization by instantaneous photomagnetic pulses," *Nature*, vol. 435, no. 7042, pp. 655–657, 2005.

[17] R. Fiederling, M. Keim, G. Reuscher, et al., "Injection and detection of a spin-polarized current in a light-emitting diode," *Nature*, vol. 402, no. 6763, pp. 787–790, 1999.

[18] A. T. Hanbicki, B. T. Jonker, G. Itskos, G. Kioseoglou, and A. Petrou, "Efficient electrical spin injection from a magnetic metal/tunnel barrier contact into a semiconductor," *Applied Physics Letters*, vol. 80, no. 7, pp. 1240–1242, 2002.