A proposal for a spin-polarized solar battery

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A solar cell illuminated by circularly-polarized light generates charge and spin currents. We show that the spin polarization of the current significantly exceeds the spin polarization of the carrier density for the majority carriers. Based on this principle we propose a semiconductor spin-polarized solar battery and substantiate our proposal using analytical arguments and numerical modeling.

Illumination of a semiconductor sample by circularly-polarized light results in a spin polarization of the carriers [1]. Optical spin polarization of both minority (optical orientation) and majority (optical pumping) carriers has been realized [1]. Introducing spin into semiconductors has also been reported by injecting spin-polarized carriers from a magnetic material (metal [2] or semiconductor [3]). Combined with the existence of reasonably long spin-relaxation times [4,5], this makes a strong case for an all-semiconductor spintronics (traditional spintronic devices are metallic [6], suitable for their use in magnetic read heads and computer memory cells). The advantages of semiconductor spintronics would be an easier integration with the existing semiconductor electronics and more versatile devices; for example, information storage and processing could, in principle, be possible on the same spintronic chip. There already exist theoretical proposals for semiconductor unipolar spin transistors and spin diodes [7,8], and bipolar semiconductor devices based on the spin-polarized p-n junction [9]. Related experimental advances, demonstrating spin-polarized light-emitting diodes [9] and a gate-voltage tunable magnetization in magnetic semiconductors [10], as well as the fabrication of a magnetic p-n junction [10], provide further motivation to explore all-semiconductor spintronics.

In this paper we propose a spin-polarized solar battery as a source of both charge and spin currents. For its operation it is necessary to have spin imbalance in carrier population (or in the corresponding components of current) as well as a built-in field which separates the carrier population (or in the corresponding components) [11]. Spin-polarization is pumped into the majority region [11,12], giving an electron lifetime $\tau_n$ of 2 ns, and a hole lifetime $\tau_p$ of 0.6 ns. Spin relaxation time (which is the spin lifetime in the n-region) is $T_1 = 0.2$ ns. In the p-region electron spin decays on...

![Diagram](image-url)
the time scale of \( \tau_s = T_1 \tau_n / (T_1 + \tau_n) \approx 0.067 \text{ ns} \). The minority diffusion lengths are \( L_n = (D_n \tau_n)^{0.5} \approx 1 \mu \text{m} \) for electrons in the p-region, and \( L_p = (D_p \tau_p)^{0.5} \approx 0.25 \mu \text{m} \) for holes in the n-region. The spin decays on the length scale of \( L_s^2 = (D_s \tau_s)^{0.5} \approx 0.8 \mu \text{m} \) in the p- and \( L_s^2 = (D_s \tau_s)^{0.5} \approx 1.4 \mu \text{m} \) in the n-region. At no applied voltage, the depletion layer formed around \( x_d = L/2 = 6 \mu \text{m} \) has a width of \( d \approx 0.9 \mu \text{m} \), of it \( d_p = (5/8)d \) in the p-side and \( d_n = (3/8)d \) in the n-side.

Let the sample be uniformly illuminated with a circularly-polarized light with photon energy higher than the band gap (bipolar photogeneration). The pair generation rate is chosen to be \( G = 3 \times 10^{23} \text{ cm}^{-3} \text{ s}^{-1} \) (which corresponds to a concentrated solar light of intensity about 1 W cm\(^{-2}\) s\(^{-1}\)), so that in the bulk of the p-side there are \( \Delta n = G \tau_n \approx 3 \times 10^{13} \text{ cm}^{-3} \) nonequilibrium electrons and holes; in the n-side the density is \( \Delta p = G \tau_p = 1.8 \times 10^{13} \text{ cm}^{-3} \). Band structure of GaAs allows a 50\% spin polarization of electrons excited by a circularly polarized light, so that the spin-polarization at the moment of creation is \( \alpha_0 = G_s / G = 0.5 \), where \( G_s = G_{\uparrow} - G_{\downarrow} \) is the difference in the generation rates of spin up and down electrons. For a homogeneous doping, the spin density in the p-side would be \( s_p = G_s \tau_s \approx 1 \times 10^{13} \text{ cm}^{-3} \), while in the n-side \( s_n = G_s T_1 \approx 3 \times 10^{13} \text{ cm}^{-3} \).

Holes in GaAs can be considered unpolarized, since they lose their spin on the time scale of momentum relaxation (typically a picosecond). The physical situation and the geometry are illustrated in Fig. 1, bottom.

We solve numerically the drift-diffusion equations for inhomogeneously doped spin-polarized semiconductors \([14]\) to obtain electron and hole densities \( n \) and \( p \), spin density \( s = n_{\uparrow} - n_{\downarrow} \) (where \( n_{\uparrow} \) and \( n_{\downarrow} \) are spin up and down electron densities), and charge \( J \) and spin \( J_s = J_{\uparrow} - J_{\downarrow} \) (where \( J_{\uparrow} \) and \( J_{\downarrow} \) are spin up and down electron charge currents) current densities. We consider ideal Ohmic contacts attached at both ends of the sample, providing infinite carrier and spin recombination velocities (so that both nonequilibrium carrier densities and spin density vanish at \( x = 0 \) and \( x = L \)). Our sample is large enough (compared to \( L_n, L_p, \) and \( L_s \)) to distinguish the bulk from the boundary effects, so the behavior of more realistic boundary conditions (which would include finite surface recombination velocities for both nonequilibrium carriers and spin) can be readily deduced from our results.

Calculated spatial profiles of carrier and spin densities, as well as carrier and current polarizations \( \alpha = n/s \) and \( \alpha_s = J_s/J \), are in Fig. 2. There is no applied voltage \( V \), but the illumination produces a reverse photo current \( J_{\text{photo}} = eG(L_n + L_p + d) \approx -11 \text{ A cm}^{-2} \) (see also Fig. 3). The behavior of currier densities is the same as in the unpolarized case (spin polarization in nondegenerate semiconductors does not affect charge currents, as diffusivities for spin up and down carriers are equal). The spin density essentially follows the nonequilibrium electronic density in the p-side, sharply decreases in the depletion layer, while then rapidly increasing to a value larger than the normal excitation value in the n-side, \( s_n \). We interpret this as a result of spin pumping through the minority channel \([14]\): electron spin excited within the distance \( L_p \) from the depletion region, as well as generated inside that region, is swept into the n-side by the built-in field, thus pumping spin polarization into the n-region. In the rest of the n-region, spin density decreases, until it reaches zero at the right boundary. Carrier spin polarization \( \alpha \) is reasonably high in the p-side, but diminishes in the n-side. [Note that in the geometry considered in \([14]\) (top of Fig. 1), for a higher illumination intensity and short junction, spin polarization remains almost unchanged through the depletion layer, a result of a much more effective electronic spin pumping.] Current polarization, however, remains quite large throughout the sample. It changes sign in the p-region (note that \( \alpha_s = J_s/J \), and since \( J(V = 0) = J_{\text{photo}} < 0 \) is a constant, \( \alpha_s \) shows the negative profile of spin current), and has a symmetric shape in the n-region, being much larger than \( \alpha \).

The profile of the carrier densities can be understood from the ideal solar cell model, based on minority carrier diffusion, and Shockley boundary conditions \([13]\) (which, for \( V = 0 \), states that the nonequilibrium carrier density vanishes at the edges of the depletion layer). We do not write the formulas here, but we plot the analytical results in Fig. 2. The behavior of \( s(x) \) can be understood along similar lines. Outside the depletion region we can
neglect the electric field as far as spin transport is considered (one does not distinguish minority and majority spins–spin is everywhere out of equilibrium, and it can be treated similarly to minority carrier densities). The equation for spin diffusion is \( D_s \frac{d^2 s}{dx^2} = (wp+1/T_1)s - G_s \). Consider first the \( p \)-region. The boundary conditions are \( s(0) = 0 \) (the ideal Ohmic contact) and \( s(x_p) = 0 \), where \( x_p = x_d - d_p \) is the point where, roughly, the depletion layer begins (see Fig. 3). The latter condition is an analogue of the Shockley condition that says that the photogenerated minority carrier density vanishes at the edges of the depletion layer, as carriers generated there are immediately swept into the other side of the layer by the built-in field. The same reasoning holds for spin, as spin is carried by the photogenerated electrons. The resulting spin density is

\[
s(x) = s_p \left[ \frac{\cosh(\xi_p) - 1}{\sinh(\xi_p)} \sin(\xi) - \cosh(\xi) + 1 \right],
\]

where \( \xi = x/L_p^s \) and \( \xi_p = x_p/L_p^s \). The spin current \( J_s = \alpha_s J = eD_s \frac{ds}{dx} \). These analytical results, plotted in Fig. 3 agree with numerical calculation. Note that near the Ohmic contact spin polarization \( \alpha(x \rightarrow 0) = \alpha_0(\tau_s/\tau_n)^{0.5} \approx 0.41 \), which is larger than the bulk value of \( \alpha_0(\tau_s/\tau_n) \approx 0.33 \). The change in sign of \( J_s \) is related to the increase of \( s \) with increasing \( x \), at small \( x \), and then decrease close to the depletion layer. Current polarization is \( \alpha_s(0) = -\alpha_0 L_p^s/(L_n + L_p + d) \approx -0.19 \) and \( s(x_p) = \alpha_s(0) \).

In the \( n \)-region, the right boundary value is that of an Ohmic contact, \( s(L) = 0 \), but at the left it is a finite value \( s(x_n) = s_0 \) (where \( x_n \) is the depletion region boundary with the \( n \)-side, \( x_n = x_d + d_n \), determined below). The solution of the diffusion equation is

\[
s(x) = s_n \left[ \frac{\cosh(\eta_n) - 1}{\sinh(\eta_n)} \sin(\eta) - \cosh(\eta) + 1 \right],
\]

where \( \eta = (L - x)/L_n^s \) and \( \eta_n = (L - x_n)/L_n^s \). To obtain \( s_0 \), consider the physics which leads to its final value. In an ideal case, all the electron spin generated in the \( p \)-region within the distance \( L_p^s \) from the depletion layer, as well as generated within the depletion layer, flow without relaxation into the \( n \)-region.

Then the boundary condition for the spin current at \( x_n \) reads \( J_s(x_n) = -eG_s(L_p^s + d) \). Since, at the same time, \( J_s(x_n) = eD_n \frac{ds}{dx}|_{x_n} \), from Eq. 3 we obtain \( s_0 = s_n [1 + \tanh(\eta_n)](L_p^s + d)/L_n^s - 1/\sinh(\eta_n) \). In general, for a long junction (\( \eta_n \gg 1 \)), \( s_0 = G_s T_1[1 + (L_p^s + d)/L_n^s] \), and the enhancement of spin due to the minority electron spin pumping is particularly large for reverse biased samples with large \( d \). For a short junction (\( \eta_n \ll 1 \)), \( s_0 = s_n \eta_n (L_p^s + d)/L_n^s \), and the spin at \( x_n \) is solely due to electron spin pumping (but its value is smaller than for a long junction). In our case \( s_0 \approx 2.2s_n \), and \( s(x) \) (Eq. 3), plotted in Fig. 3 gives a very good agreement with numerical data. Spin polarization of the current at the Ohmic contact is \( \alpha_s(L) = \alpha_0 L_p^s/L_n + L_p + d \approx 0.33 \), while at \( x_n \) is \( \alpha_s(x_n) = \alpha_0 [L_p^s + d]/(L_n + L_p + d) \approx 0.39 \). Current polarization is much larger than carrier polarization, since both spin and charge currents are mainly diffusive. If only the \( p \)-region would be illuminated with photogenerated spin density \( G_s \), the induced spin density in the \( n \)-region would be \( s_0 = G_s(T_1/\tau_n)^{0.5} \tanh(\eta_n) \). This is purely the minority-electron spin pumping effect. It is most effective for long junctions, where the spin amplification is \( s_0/s_p = (T_1/\tau_n)^{0.5} = (1 + T_1/\tau_n)^{0.5} \). At low temperatures \( T_1 \) can be larger than \( \tau_n \) by orders of magnitude, and so spin amplification can be significant.

Finally, in Fig. 3 we plot the I-V characteristics of the charge and spin currents. The resulting charge I-V curve under illumination can be, as in standard solar cells, understood as the effect of superposition of the negative short circuit current (reverse photo current \( J_{\text{photo}} \)) and the dark current, exponentially increasing with forward voltage. The total charge current vanishes at the open-circuit voltage of about 1 V. As spin current is not conserved (it varies in space), we choose two points to represent it on the I-V plot. One is the value of \( J_s \) at the right boundary, the other at the point where spin is maximum (at the right edge of the depletion layer; this is an important point when a short junction would be considered). Both values decrease in magnitude with increasing voltage, as a result of decreasing of the effect of spin pumping from the nonequilibrium minority electrons. This is much more pronounced in the case of \( J_s \) at maximum \( s \), which is most sensitive to the electronic pumping, as it varies with \( d \) (which decreases with increasing voltage).
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