Complete spin polarization of electrons in semiconductor layers and quantum dots

V. V. Osipov\textsuperscript{1,2}, A. G. Petukhov\textsuperscript{3}, and V. N. Smelyanskiy\textsuperscript{2}

\textsuperscript{1}New Physics Devices, LLC, 2041 Rosecrans Avenue, El Segundo, CA 90245
\textsuperscript{2}NASA Ames Research Center, Mail Stop 269-3, Moffett Field, CA 94035
\textsuperscript{3}Physics Department, South Dakota School of Mines and Technology, Rapid City, SD 57701

(Dated: March 23, 2022)

We demonstrate that non-equilibrium electrons in thin nonmagnetic semiconductor layers or quantum dots can be fully spin polarized by means of simultaneous electrical spin injection and extraction. The complete spin polarization is achieved if the thin layers or quantum dots are placed between two ferromagnetic metal contacts with moderate spin injection coefficients and antiparallel magnetizations. The sign of the spin polarization is determined by the direction of the current. Applications of this effect in spintronics and quantum information processing are discussed.

PACS numbers: 72.25.Hg, 72.25.Mk

Spintronics is a new field of condensed matter physics based on manipulation of electron spins in solids\textsuperscript{1,2}. Injection of spin-polarized electrons into nonmagnetic semiconductors (NS) is of particular interest because of the relatively large spin-coherence lifetime, $\tau_s$, in NS\textsuperscript{1,2} and promising applications for ultrafast, low-power spin devices\textsuperscript{1,2,8,9,10,11,12} and for spin-based quantum information processing (QIP)\textsuperscript{2,6}. Both the characteristics of the spintronic devices and fidelities of various spin-based QIP schemes dramatically improve when spin polarizations\textsuperscript{1,2} are achieved. Nonetheless, the greatest value of electrons with spin $\sigma = \uparrow$ through the contacts can be written as

$$J_{\uparrow}(0) = J(1 + \gamma_L)/2, \quad J_{\uparrow}(w) = J(1 + \gamma_R)/2,$$

where $J_{\uparrow}(0)$ and $J_{\uparrow}(w)$ are the currents in the $n$-NS layer at the boundaries with the right and left contacts $x = 0$ and $x = w$ (Fig.1). The continuity equation reads

$$dJ_{\uparrow}/dx = q\delta n_{\uparrow}/\tau_s,$$

where $\delta n_{\uparrow} = n_{\uparrow} - n_S/2$, $n_S$ is the total electron density and $n_{\uparrow}$ is the density of up-electrons. Obviously $\delta n_{\uparrow}(x) \simeq \text{const}$ in the $n$-NS layer when its thickness $w \ll L_s$, where $L_s$ is the spin diffusion length. Integrating Eq. (2) over $x$ from 0 to $w$, we obtain $J_{\uparrow}(w) - J_{\uparrow}(0) = qw\delta n_{\uparrow}/\tau_s$, and using (1) and $\delta n_{\uparrow}(x) = -\delta n_{\downarrow}(x)$ we find the spin polarization in thin $n$-NS layer:

$$P_n(x) = (\delta n_{\uparrow} - \delta n_{\downarrow})/n_S \simeq (\gamma_R - \gamma_L)J_{\uparrow}/J_w \equiv P_n,$$

where $J_w = qn_S/\tau_s$. One can see from (3) that: $P_n = 0$ when $\gamma_R = \gamma_L$, since in this case the currents of up- and down electrons through the right and left contacts are the same: $J_{\uparrow}(0) = J_{\uparrow}(w)$. On the contrary when $\gamma_R \neq \gamma_L$ the value $|P_n|$ → 1 when $J \rightarrow J = J_w/(|\gamma_R| - |\gamma_L|)$. For example, if $\gamma_L < 0$ and $\gamma_R > 0$, i.e. magnetizations $M_1$ and $M_2$ in FM have opposite directions, Fig.1(a), $P_n = (|\gamma_R| + |\gamma_L|)J_{\uparrow}/J_w$, i.e. $P_n \rightarrow 1$ as $J \rightarrow J = J_w/(|\gamma_R| + |\gamma_L|)$. Thus, due to the difference of the currents of spin polarized electrons through the contacts, the spin density $P_n$ in the $n$-NS layer increases with the current and can
reach 100% even at small spin injection coefficients. One can see from [4] that the inversion of the current results in the opposite sign of \( P_n \). These findings are valid for both degenerate and nondegenerate semiconductors. In these FM-NS-FM junctions [16], weak dependence of \( \gamma \) in FM-NS junctions when the \( n \) [16] can strongly depend on \( J \) [11,12] in FM-NS junctions when the \( n \)-NS region and thin (\( \delta \)-doped) \( n \)-layer are both nondegenerate semiconductors. In these FM-NS-FM junctions \( P_n \) attains the value \( P_n = (\gamma_R - \gamma_L)/(-1 - \gamma_R \gamma_L) \) for \( J > J_S \) and \( w \ll L_{1,2} \). One can see that \( \gamma_R \) and \( \gamma_L \) determine a particular value of the threshold current, \( J_t \), but it does not alter the main result: \( |P_n| \rightarrow 1 \) as \( J \rightarrow J_t \). The only requirement is a relatively weak dependence of \( \gamma_R \) and \( \gamma_L \) on \( J \). This condition can be fulfilled, for example, when thin, heavily-doped \( n \)-layers are formed between \( n \)-NS and FM regions, Fig. 1. The parameters of \( n \)-layers have to satisfy certain conditions [16]. In particular, the electron gas must be degenerate in a certain part of the \( n \)-layer and the transition between the \( n \)-S and \( n \)-NS layers must be step-like. This situation is realized when the \( n \)-S layers have energy bandgaps narrower than that of the \( n \)-S region, Fig. 1(b), or when an additional \( \delta \)-doped acceptor layer is formed between the \( n \)-S and \( n \)-NS regions. Due to a high density of electrons in the \( n \)-S layer, \( \gamma \) of such FM-\( n \)-S contacts weakly depends on \( J \) up to the currents significantly exceeding \( J_t \), Weak dependence of \( \gamma \) on \( J \) is also realized in FM-NS junctions with highly degenerate accumulation layers formed in \( n \) near the FM-NS interface. This situation has been studied extensively in Refs. [3,5,8,9,10] and has been realized experimentally in Fe-InAs junctions [14].

We note that \( \gamma \) [17] can strongly depend on \( J \) [11,12] in FM-NS junctions when the \( n \)-NS region and thin (\( \delta \)-doped) \( n \)-layer are both nondegenerate semiconductors. In these FM-NS-FM junctions \( P_n \) attains the value \( P_n = (\gamma_R - \gamma_L)/(-1 - \gamma_R \gamma_L) \) for \( J > J_S \) and \( w \ll L_{1,2} \). One can see that \( P_n = 0.6 \) at \( \gamma_R = -\gamma_L = 0.33 \), i.e. even in this case \( P_n \) can exceed the spin injection coefficients of the FM-S junctions. In degenerate semiconductors the diffusion constants of up- and down-electrons are different and depend on electron densities. As a result, \( \delta n_\uparrow(x) \) is described by a diffusion-drift equation with a bi-spin diffusion constant \( D(P_n) \) which goes to zero when \( |P_n| \rightarrow 1 \). Therefore, in degenerate NS, the spatial variation of \( P_n(x) \) is sharper and its current dependence is stronger than those in nondegenerate NS [cf. yellow and red curves.

\[
\delta n_\uparrow(x) = (n_S/2)(c_1 e^{-x/L_1} + c_2 e^{-(w-x)/L_2}), \quad (4)
\]

It follows from [18] that \( P_n(0) \) or \( P_n(w) \) reaches 1 at \( J = J_t(\gamma_L, \gamma_R, w) \). The spatial dependence of \( P_n(x) \) is very weak for \( w \ll L_s \) and \( P_n(x) \approx P_n \) as in Eq. [3].

One can see from [18] and [12] that \( \gamma_R \) and \( \gamma_L \) determine a particular value of the threshold current, \( J_t \), but it does not alter the main result: \( |P_n| \rightarrow 1 \) as \( J \rightarrow J_t \). The only requirement is a relatively weak dependence of \( \gamma_R \) and \( \gamma_L \) on \( J \). This condition can be fulfilled, for example, when thin, heavily-doped \( n \)-layers are formed between \( n \)-NS and FM regions, Fig. 1. The parameters of \( n \)-layers have to satisfy certain conditions [16]. In particular, the electron gas must be degenerate in a certain part of the \( n \)-layer and the transition between the \( n \)-S and \( n \)-NS layers must be step-like. This situation is realized when the \( n \)-S layers have energy bandgaps narrower than that of the \( n \)-S region, Fig. 1(b), or when an additional \( \delta \)-doped acceptor layer is formed between the \( n \)-S and \( n \)-NS regions. Due to a high density of electrons in the \( n \)-S layer, \( \gamma \) of such FM-\( n \)-S contacts weakly depends on \( J \) up to the currents significantly exceeding \( J_t \). Weak dependence of \( \gamma \) on \( J \) is also realized in FM-NS junctions with highly degenerate accumulation layers formed in \( n \) near the FM-NS interface. This situation has been studied extensively in Refs. [3,5,8,9,10] and has been realized experimentally in Fe-InAs junctions [14].

We note that \( \gamma \) [17] can strongly depend on \( J \) [11,12] in FM-NS junctions when the \( n \)-NS region and thin (\( \delta \)-doped) \( n \)-layer are both nondegenerate semiconductors. In these FM-NS-FM junctions \( P_n \) attains the value \( P_n = (\gamma_R - \gamma_L)/(-1 - \gamma_R \gamma_L) \) for \( J > J_S \) and \( w \ll L_{1,2} \). One can see that \( P_n = 0.6 \) at \( \gamma_R = -\gamma_L = 0.33 \), i.e. even in this case \( P_n \) can exceed the spin injection coefficients of the FM-S junctions.
in Fig. 1(c)]. For example, at \( w = 0.1L_s \) and currents \( J = J_t \) the polarization changes in the ranges 
\( 1 > P_n(x) > 0.984 \) or \( 1 > P_n(x) > 0.954 \) for nondegenerate NS and \( 1 > P_n(x) > 0.91 \) or \( 1 > P_n(x) > 0.85 \) for degenerate NS when \( \gamma_R = -\gamma_L = 0.3 \) or \( \gamma_R = -\gamma_L = 0.1 \), respectively.

At high currents when \( J > J_t \) [see e.g. (8) and (9)] the value \( |P_n| = 2|\delta n_{ij}|/n_S = \langle 2n_{ij} - n_S \rangle /n_S \) is higher than 1, i.e. spin density either near \( x = 0 \) or near \( x = w \) exceeds \( n_S \). This means that the used condition of neutrality \( n_1 + n_4 = n_S \), i.e. \( \delta n_{ij}(x) = -\delta n_{ij}(x) \), is violated and a negative space charge accumulates near one of the boundaries. This charge will increase the voltage drop \( V_S \) across \( n \)-NS region. This conclusion follows from numerical analysis of our system of equations which includes: Eq. (2), \( J = J_t(x) + J_1(x) = \text{const} \), \( J_s = q\mu_n E + qD_{ns}dn_s/dx \), and the Poisson’s equation, \( \varepsilon\varepsilon_0dE/dx = q(n_s - n_1 - n_4) \).

The FM-$n^+ -$n-$n^+ \text{-FM}$ heterostructures under consideration are supersensitive spin valves. Indeed, as we noticed above [see (3) and (5)], \( P_n \approx 0 \) and \( \delta n_{ij}(x) \approx 0 \) when \( w < L_s \) and \( \gamma_R = \gamma_L \), i.e. when the magnetizations \( M_1 \) and \( M_2 \) in the FM layers have the same direction. In this case, \( V_S = V_ohm = Jw/q\mu_nS \) at any current. When \( \gamma_R \neq \gamma_L \) the space charge arises in the \( n \)-S region at \( J > J_t \) and \( V_{NS} \) exceeds \( V_ohm \) significantly. Thus, inversion of direction of \( M_1 \) or \( M_2 \) and also precession of electron spin in the \( n \)-S region have to change the voltage \( V_S \) to a much greater extent than in the structures considered in Refs. [3]. The use of the FM-$n^+ -$n-$n^+ \text{-FM}$ heterostructures in different spin-based devices 1, 2, 3, 4, 5 should result in dramatic improvement of their characteristics due to the high spin polarization of electrons in the \( n \)-NS layer.

A more complex FM-$n^+ -$n-$n^+ \text{-FM}$ heterostructure is shown in Fig. 2(a). High spin polarization of electrons arises in a thin \( n \)-S layer 1 grown on highly resistive wide-bandgap semiconductor layer 3 when the current flows between ferromagnetic regions FM$1$ and FM$2$. Such a heterostructure can be utilized modernize various spin-based nanodevices presented in Refs. [3] such as ultrasound magnetic sensors, transistors, square law detectors, and frequency multipliers. It can also be used for 100\% spin polarization of electrons in quantum dots 5 localized in the layer 3 grown on a semiconductor substrate 4 having the same bandgap as the layer 1. This effect can be realized at very low temperatures even when the spin polarization inside the \( n \)-S layer 1 is less than 100\%, e.g. \( P_n \approx 60\%-80\% \). Indeed, let us consider quantum dots (QD) (regions (5) in Fig. 2(a) with band offset \( \Delta E_c = E_{c5} - E_{c3} < 0 \) that are placed inside of a two-dimensional potential barrier (semiconductor layer (3) with band offset \( \Delta E_c = E_{c3} - E_{c1} > 0 \)). As we noted above, the spin polarization \( P_n \) and density of up-electrons, \( n_{1u} \), increase with current \( J \) between FM$1$ and FM$2$ contacts when \( \gamma_L < 0 \) and \( \gamma_R > 0 \). This means that the quasi-Fermi level for the up-electrons \( E_{F_1} \) increases and \( E_{F_2} \) for down-electrons decreases with \( J \). At a certain current \( F_2 \) can exceed \( \Delta E_c \) and only the up-electrons will populate the layer 3 and will be captured by QDs. Thus, at very low temperatures the electron polarization in the QDs should be extremely close to 1, \( 1 - P_n \approx \exp\left[ -(E_{c3} - F_1)/T \right] \ll 1 \). The spin polarization of electrons in QDs can be realized after their recombination with photogenerated holes or holes injected from \( p \)-region, shown in Fig. 2a. This effect can be used for efficient polarization of nuclear spins in QDs. The sign of the spin polarization of electrons in the \( n \)-NS layer (1) and in QDs can be reversed by simple inversion of the current direction between FM$1$ and FM$2$ contacts, Fig. 2(a). Thus, the considered effects have a potential for changing the development strategy for various spin-based devices and QIP schemes.

This work is supported by NASA ITS program (V. O. and V. S.) and NSF (A. P.).
[1] I. Zutic, J. Fabian, and S. Das Sarma, Rev. Mod. Phys. 76, 323 (2004).
[2] Semiconductor Spintronics and Quantum Computation, edited by D. D. Awschalom, D. Loss, and N. Samarth (Springer, Berlin, 2002).
[3] S. Datta and B. Das, Appl. Phys. Lett. 56, 665 (1990); S. Gardelis et al., Phys. Rev. B 60, 7764 (1999).
[4] R. Sato and K. Mizushima, Appl. Phys. Lett. 79, 1157 (2001); X. Jiang et al., Phys. Rev. Lett. 90, 256603 (2003).
[5] V. V. Osipov and A. M. Bratkovsky, Appl. Phys. Lett. 84, 2118 (2004); A. M. Bratkovsky and V. V. Osipov, Phys. Rev. Lett. 92, 098302 (2004) and Appl. Phys. A 80, 1 (2005).
[6] M. A. Nielsen and I. L. Chuang, Quantum Computation and Quantum information (Cambridge University Press, Cambridge, 2000).
[7] A. G. Aronov and G. E. Pikus, Fiz. Tekh. Poluprovodn. 10, 1177 (1976) [Sov. Phys. Semicond. 10, 698 (1976)].
[8] M. Johnson and R. H. Silsbee, Phys. Rev. B 35, 4959 (1987); M. Johnson and J. Byers, ibid. 67, 125112 (2003).
[9] E. I. Rashba, Phys. Rev. B 62, R16267 (2000).
[10] Z. G. Yu and M. E. Flatté, Phys. Rev. B 66, R201202 and 235302 (2002).
[11] V. V. Osipov and A. M. Bratkovsky, Phys. Rev. B 70, 205312 (2004).
[12] A. M. Bratkovsky and V. V. Osipov, J. Appl. Phys. 96, 4525-4529 (2004).
[13] A. T. Hanbicki et al., Appl. Phys. Lett. 80, 1240 (2002); A. T. Hanbicki et al., ibid. 82, 4092 (2003).
[14] H. Ohno et al., Jpn. J. Appl. Phys. 42, L1 (2003).
[15] S. M. Sze, Physics of Semiconductor Devices (Wiley, New York, 1981).
[16] V. V. Osipov, V. N. Smelyanskiy, and A. G. Petukhov, unpublished; V. V. Osipov and A. M. Bratkovsky, cond-mat/0504494 (2005).
[17] Note that $\gamma$ is denoted as $P_J$ in Refs. 3, 11, 12 and is called current spin polarization of FM-NS contact.