

Multi-quantum-well spin oscillator

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(Received 27 June 2007; accepted 3 August 2007; published online 27 August 2007)

A dc voltage biased II-VI semiconductor multi-quantum-well structure attached to normal contacts exhibits self-sustained spin polarized current oscillations if one or more of its wells are doped with Mn. Without magnetic impurities, the only configurations appearing in these structures are stationary. Analysis and numerical solution of a nonlinear spin transport model yield the minimal number of wells (four) and the ranges of doping density and spin splitting needed to find oscillations. © 2007 American Institute of Physics. [DOI: 10.1063/1.2775812]

Among spintronics challenges, electrical injection of spin polarized current in semiconductor nanostructures is important due to their potential applications as spin-based devices.^{1,2} Different spin injectors have been proposed, including ferromagnetic contacts or semimagnetic semiconductor contacts with large g factors that are polarized by a magnetic field at low temperatures. The efficiency of ferromagnetic/semiconductor junctions has been shown to be very small due to the large conductivity mismatch between the metal and the semiconductor.³ Diluted magnetic semiconductors (DMSs) are much more efficient as spin injectors, as it has been shown for contacts based in Mn.⁴⁻⁶

Much theoretical and experimental work⁷⁻¹⁰ is devoted to the analysis of nonlinear transport through conventional semiconductor superlattices (SLs), in which the interplay between Coulomb interaction, electron confinement, and dc voltage produces very interesting properties such as formation of electric field domains (EFDs) and self-sustained current oscillations (SSCOs). In addition, external ac electric fields produce additional features in the nonlinear I/V curve such as photoassisted EFDs and absolute negative differential resistance in the nonadiabatic limit¹⁰ or, at low ac frequencies, chaotic current oscillations.¹¹⁻¹³

Compared to conventional semiconductor nanostructures, DMSs present an additional degree of freedom: the spin, which plays an important role in electron dynamics, in particular, II-VI based semiconductor SLs doped with Mn⁺⁺ ions.¹⁴ In these systems, carrier-ion exchange spin effects dominate the magnetotransport, producing spin polarized transport and large magnetoresistance. Exchange interaction between the spin carrier and Mn ions results in large spin splittings. In fact, full spin polarization has been achieved at magnetic fields of 1 T. Recently,¹⁵ nonlinear transport through DMS SLs has been investigated. The interplay be-

tween the nonlinearity of the current-voltage characteristics and the exchange interaction produces interesting spin dependent features:¹⁵ multistability of steady states with different polarizations in the magnetic wells, time-periodic oscillations of the spin polarized current, and induced spin polarization in nonmagnetic wells by their magnetic neighbors, among others. The high sensitivity of these systems to external fields points out to their potential application as magnetic sensors.¹⁵

In this letter, we analyze nonlinear electron spin dynamics of a n -doped dc voltage biased semiconductor multi-quantum-well structure (MQWS) having one or more of its wells doped with Mn. We show that spin polarized current can be obtained even using normal contacts, provided one quantum well (QW) is doped with magnetic impurities (Mn). We analyze under which conditions the system exhibits static EFDs and stationary current or moving domains and time-dependent oscillatory current. SSCOs appear in nanostructures with at least four QWs. Moreover, SSCOs may appear or not depending on the spin splitting Δ induced by the exchange interaction. From our results, we propose how to design a device behaving as a spin polarized current oscillator.

Our sample configuration consists of a n -doped ZnSe/(Zn,Cd,Mn)Se weakly coupled MQWS. The spin for the magnetic ion Mn⁺⁺ is $S=5/2$ and the exchange interaction between the Mn local moments and the conduction band electrons is ferromagnetic in II-VI QWs. Using the virtual crystal and mean field approximations, the effect of the exchange interaction is to make the subband energies spin dependent in those QWs that contain Mn ions: $E_j^\pm = E_j \mp \Delta/2$ where $\Delta = 2J_{sd}N_{Mn}SB_S(g\mu_B B_S/(k_B T_{eff}))$ for spin $s = \pm 1/2$, and B , J_{sd} , N_{Mn} , and T_{eff} are the external magnetic field, the exchange integral, the density of magnetic impurities, and an effective temperature which accounts for Mn interactions, respectively.^{15,16} We model spin-flip scattering coming from spin-orbit or hyperfine interaction by means of a phenom-

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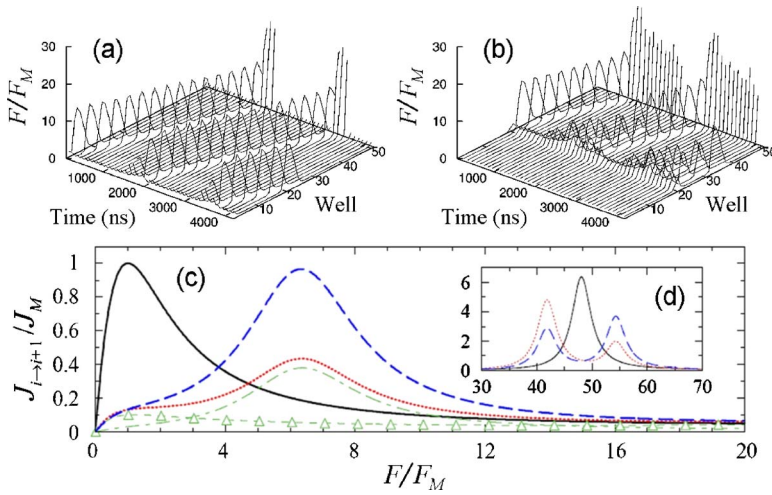


FIG. 1. (Color online) Electric field distribution if the magnetic QW is (a) $i=1$, (b) $i=20$. (c) Solid line: $J_{i \rightarrow i+1}(F)$ for nonmagnetic i and $i+1$. For magnetic i , nonmagnetic $i \pm 1$: $J_{i \rightarrow i+1}$ (dotted line), $J_{i+1 \rightarrow i}$ (dot-dashed line), $J_{i \rightarrow i+1}^+$ (triangles), and $J_{i-1 \rightarrow i}$ (dashed line). (d) Same at larger electric fields. Parameter values: $N=50$, $V=0.048$ V, $N_D=10^{10}$ cm $^{-2}$, $F_M=0.64$ kV/cm, and $J_M=0.409$ A/cm 2 .

enological scattering time τ_{sf} , which is larger than impurity and phonon scattering times: $\tau_{scat}=\hbar/\gamma < \tau_{sf}$. Vertical transport in the MQW is spin-independent sequential tunneling between adjacent QWs, so that when electrons tunnel to an excited state they instantaneously relax by phonon scattering to the ground state, with the same spin polarization. Lastly, electron-electron interaction is considered within the Hartree mean field approximation. The equations describing our model generalize those in Ref. 15 to the case of finite T :

$$F_i - F_{i-1} = \frac{e}{\epsilon} (n_i^+ + n_i^- - N_D), \quad (1)$$

$$e \frac{dn_i^\pm}{dt} = J_{i-1 \rightarrow i}^\pm - J_{i \rightarrow i+1}^\pm \pm \frac{A(n_i^+, n_i^-, \mu_i^\pm)}{\tau_{sf,i}}, \quad (2)$$

$i=1, \dots, N$. $A(n_i^+, n_i^-, \mu_i^\pm) = n_i^- - n_i^+ / \alpha_i$, with $\alpha_i = 1 + \exp[(E_{1,i}^- - \mu_i^+) / \gamma_\mu]$. As $\gamma_\mu \rightarrow 0$, $A(n_i^+, n_i^-, \mu_i^\pm)$ becomes $\pm(n_i^- - n_i^+) / \tau_{sf}$ for $\mu_i^\pm > E_{1,i}^\pm$ (equivalently, $\mu_i^+ - E_{1,i}^+ > \Delta$), and $\pm n_i^- / \tau_{sf}$ otherwise.¹⁵

Here, n_i^+ , n_i^- , $-F_i$, and μ_i^\pm are the two-dimensional spin-up and spin-down electron densities, the average electric field, and the chemical potential at the i th SL period (which starts at the right end of the $(i-1)$ th barrier and finishes at the right end of the i th barrier), respectively. $E_{j,i}^\pm$ are the spin-dependent subband energies (measured from the bottom of the i th well): $E_{j,i}^\pm = E_j \mp \Delta_i / 2$, with $\Delta_i = \Delta$ or 0, depending on whether the i th well contains magnetic impurities. N_D is the 2D doping density at the QWs, ϵ is the average permittivity, $l=d+w$ with d and w the barrier and well width, and $-J_{i \rightarrow i+1}^\pm$ is the tunneling current density across the i th barrier, calculated by the transfer-Hamiltonian method:

$$J_{i \rightarrow i+1}^\pm = \frac{e v^\pm}{l} \{ n_i^\pm - \rho \ln[1 + e^{n_i^\pm / \rho - F_i / a} - e^{-F_i / a}] \}, \quad (3)$$

where $i=1, \dots, N-1$, $\rho = m^* k_B T / (2\pi\hbar^2)$, m^* is the effective electron mass and $a = k_B T / (el)$. The voltage bias condition is $\sum_{i=0}^N F_i l = V$ for the applied voltage V . For electrons with spin $\pm 1/2$, μ_i^\pm and n_i^\pm are related by $n_i^\pm = (\rho / N_D) \ln[1 + \exp[(\mu_i^\pm - E_{1,i}^\pm) / (k_B T)]]$. Defining $J_{i \rightarrow i+1} = J_{i \rightarrow i+1}^+ + J_{i \rightarrow i+1}^-$, time differencing Eq. (1) and inserting the result in Eq. (2), we obtain an expression for the total current density $J(t)$ when $dV/dt = 0$: $\epsilon dF_i/dt + J_{i \rightarrow i+1} = J(t) = (N+1)^{-1} \sum_{i=0}^N J_{i \rightarrow i+1}$. As boundary tunneling currents for $i=0$ and N , we use Eq. (3) with

$n_0^\pm = n_{N+1}^\pm = N_D / 2$ (identical normal contacts).¹⁵ Initially, we set $F_i = V / [(N+1)l]$, $n_i^\pm = N_D / 2$ (normal QWs). The spin-dependent “forward tunneling velocity” $v^\pm(F_i)$ is a sum of Lorentzians of width 2γ (the same value for all subbands, for simplicity) centered at the resonant field values $F_{j,i}^\pm = (E_{j,i}^\pm - E_{1,i}^\pm) / (el)$:⁸

$$v^\pm(F_i) = \sum_{j=1}^2 \frac{(\hbar^3 l \gamma / 2 \pi^2 m^{*2}) T_i(E_{j,i}^\pm)}{(E_{1,i}^\pm - E_{j,i+1}^\pm + eF_i l)^2 + (2\gamma)^2}. \quad (4)$$

Here, T_i is proportional to the dimensionless transmission probability across the i th barrier.⁸

We have considered a sample with $d=10$ nm, $w=5$ nm, $\Delta=15$ meV, $\tau_{sf}=10^{-9}$ s (normal QW) and 10^{-11} s (magnetic QW),¹⁷ $m^*=0.16m_0$, $\epsilon=7.1\epsilon_0$, $T=5$ K, $E_1=15.76$ meV, $E_2=61.99$ meV, $\gamma=1$ meV, and $\gamma_\mu=0.1$ meV.

There are SSCOs for a variety of configurations, but only if one or more QWs contain magnetic impurities yielding a sufficiently large spin splitting. The nonmagnetic MQWS does not exhibit self-oscillations.

Firstly, we have used long SLs ($N=50$), finding that charge dipoles are triggered at the well containing Mn that is closest to the injector. These dipoles move to the collector (near which they may become monopoles if V is large enough), disappear there, and new dipoles are triggered, producing SSCOs similar to those observed in III-V semiconductor SLs.⁸

Figures 1(a) and 1(b) show that if the only magnetic QW is the i th (with $1 \leq i < N-3$), the dipoles are emitted at this well, and their motion is limited to the last $N-i$ QWs. Why is this? Figure 1(c) depicts $J_{i \rightarrow i+1}(F, N_D/2, N_D/2)$. As $E_{1,i+1}^\pm = E_1$, $E_{1,i}^\pm = E_1 \mp \Delta/2$, the $j=1$ term in Eq. (4) is a Lorentzian centered at $F_{1,i}^\pm = \pm \Delta / (2el)$. Then, $J_{i \rightarrow i+1}$ has a peak roughly at $(\Delta^2 + 8\gamma^2) / (2el\Delta)$ (if $eF_M l \ll \Delta/2$), mostly due to $J_{i \rightarrow i+1}^+$. The height of this peak is under half that of $J_{i \rightarrow i+1}(F)$ for nonmagnetic wells (T_i is smaller for E_1^+ than for E_1^-), as depicted in Fig. 1(c). Spin splitting also causes $J_{i \rightarrow i+1}$ (for magnetic QW i) to display two peaks at $(E_2 - E_1 \pm \Delta/2) / (el)$ instead of one peak at $(E_2 - E_1) / (el)$ with their combined strength (for nonmagnetic QW i) [see Fig. 1(d)]. Similarly, if QW i is magnetic, $J_{i-1 \rightarrow i}^\pm$ has peaks at $\mp \Delta / (2el)$ and $(E_2 - E_1 \mp \Delta/2) / (el)$, contrary to the shifts in $J_{i \rightarrow i+1}^\pm$.

The shifted curves $J_{i-1 \rightarrow i}$ and $J_{i \rightarrow i+1}$ play the role of effective cathode boundary currents during SSCOs. Clearly, they intersect the current farther away from the magnetic

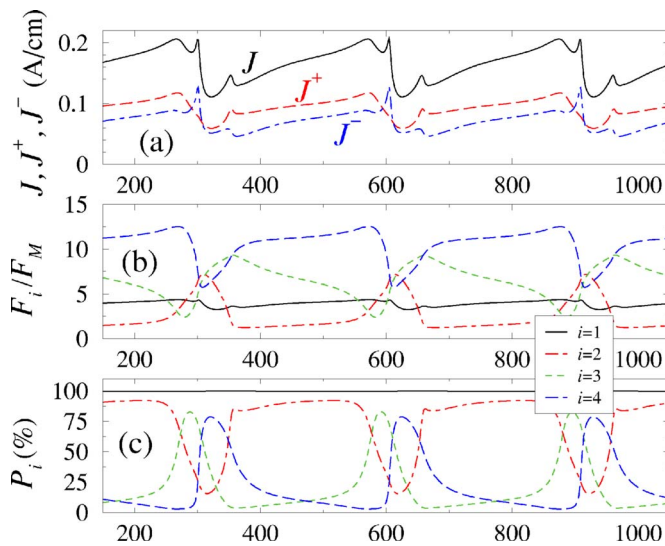


FIG. 2. (Color online) (a) Tunneling current, (b) electric field, and (c) polarization as a function of time at the i QW during SSCOs for $N=4$, $V=0.023$ V, $N_D=1.2 \times 10^{10}$ cm $^{-2}$, and $F_M=0.65$ kV/cm. Oscillation frequency is 5.4 MHz.

QW [solid line in Fig. 1(c)] on its second, decreasing branch. The intersection point corresponds to the critical current for triggering a charge dipole.^{8,9} For Fig. 1(b), the boundary current at the nonmagnetic injector is the solid line in Fig. 1(c). Such boundary condition precludes current self-oscillations due to dipole recycling. Thus, dipole recycling occurs only for the magnetic and successive QWs.

Next, we have calculated the shortest SL displaying SSCOs when only the first QW is magnetic. For our parameter values, we find SSCOs for SL having at least four periods. Figure 2 shows the total current density (most of which is due to spin-up electrons), the field, and the spin polarization $P_i=(n_i^+-n_i^-)/(n_i^++n_i^-)$ at the QWs during SSCOs for $N=4$. Note that QW $i=1$ is always fully polarized, whereas the others are strongly polarized only when the dipole wave is traversing them: their polarizations drop abruptly afterward. The fraction of the oscillation period during which the i th QW is strongly polarized decreases as i increases.

For $N \geq 4$, SSCOs appear if $N_D > N_{D,1}$. We have sought this critical doping density for $4 \leq N \leq 50$: $N_{D,1} = 2 \times 10^{10}/(N-2)$ cm $^{-2}$. In the continuum limit ($N \rightarrow \infty$), this approximate formula yields $NN_{D,1} \approx 2 \times 10^{10}$ cm $^{-2}$, according to the N - L criterion in the theory of the Gunn effect.¹⁸

Our results could be used to construct an oscillatory spin polarized current injector. Such a short device (with four QWs) would inject mostly negatively polarized current whereas long devices would inject predominantly positively

polarized current. It is important that normal contacts can be used to build the oscillator, because the crucial requirement is to dope the first QW with Mn. We have also indicated the range of N_D needed to achieve spin polarized SSCOs. For self-oscillations to occur, appropriate ranges of spin splitting should be induced by tailoring the magnetic impurity density and external magnetic fields.¹⁹

The authors thank D. Sánchez for critical reading of this letter and useful suggestions. This work has been supported by MECD Grant Nos. MAT2005-05730-C02-01 and MAT2005-06444.

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- ¹⁹For $N=4, 5, 6, 7, 10, 12, 14, 16, 18, 20$, $\Delta_c=2.66, 1.16, 1.07, 1.01, 0.94, 1.80, 2.01, 2.21, 2.40, 2.60$ meV, respectively.