Available online at www.sciencedirect.com

ScienceDirect

Physica E 40 (2008) 1099–1101

PHYSICA E

www.elsevier.com/locate/physe

Multiquantum well spin polarized current oscillator

Manuel Carretero[a,b,*], Ramón Escobedo[c], Luis L. Bonilla[a,b], Gloria Platero[d]

[a] Modeling, Simulation and Industrial Mathematics, Universidad Carlos III de Madrid, Av. Universidad, 30, Leganés, 28911, Spain
[b] Unidad Asociada al Instituto de Ciencias de Materiales de Madrid, CSIC, Spain
[c] Departamento de Matemática Aplicada, Universidad de Cantabria, Santander, 39005, Spain
[d] Instituto de Ciencia de Materiales de Madrid, CSIC, Cantoblanco, 28049, Spain

Available online 14 September 2007

Abstract

We analyze nonlinear electron spin dynamics of a n-doped DC voltage biased semiconductor II–VI multi-quantum well structure (MQWS) having one or more of its wells doped with Mn. Even if normal contacts have been attached to this nanostructure, spin polarized current can be obtained provided one well is doped with magnetic impurities. We have studied the conditions for the system to exhibit static electric field domains and stationary current or moving domains and time-dependent oscillatory current. There are self-sustained current oscillations (SSCO) for nanostructures with four or more QWs. Moreover, SSCO may appear or not depending on the spin splitting induced by both, the exchange interaction and the external magnetic field. We calculate the minimal doping density needed to have SSCO, which is crucial to design a device behaving as a spin-polarized current oscillator.

PACS: 73.21.Cd; 72.25.Dc; 72.25.Mk; 75.50.Pp

Keywords: Nonlinear charge and spin transport; Superlattice spin oscillator

1. Introduction

To use semiconductor nanostructures as spin devices, one has to solve the problem of injecting spin polarized current in them. Diluted magnetic semiconductors (DMS) are much better spin injectors than ferromagnetic or semimagnetic semiconductor junctions which have a very small efficiency due to the large conductivity mismatch between the metal and the semiconductor. For example in II–VI semiconductor MQWS doped with Mn, exchange interaction between the spin carrier and Mn ions results in large spin splitting, thereby producing spin polarized transport and large magneto-resistance. Nonlinear transport through DMS MQWS has been recently investigated, Ref. [1]. The interplay between the non-linearity of the current as a function of the DC voltage and the exchange interaction produces multi-stability of steady states with different polarization in the magnetic wells [1], time-dependent periodic oscillations of the spin-polarized current [2] and induced spin polarization in non magnetic wells by their magnetic neighbors.

2. Governing equations

The equations describing our model generalize those in Ref. [1] to the case of finite T:

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

$$e\frac{dn_i^{\pm}}{dt} = J^{\pm}_{i-1\to i} - J^{\pm}_{i\to i+1} \pm \frac{n_i^- - n_i^+ \Theta_i(\mu_i^+)}{\tau_{\rm sf,i}}, \tag{2}$$

where N, n_i^+, n_i^-, μ_i^+, $\tau_{{\rm sf},i}$ and $-F_i$ are the number of wells, the two-dimensional (2D) spin-up and spin-down electron densities, the spin-up chemical potential, the phenomenological spin-flip time (larger than impurity and phonon scattering times [1]) and the average electric field at the ith MQWS period (which starts at the right end of the $(i-1)$th

*Corresponding author. Modeling, Simulation and Industrial Mathematics, Universidad Carlos III de Madrid, Av. Universidad, 30, Leganés, 28911, Spain. Tel.: +34 91 6249409; fax: +34 91 6249129.
E-mail address: manuel.carretero@uc3m.es (M. Carretero).

1386-9477/$ - see front matter
doi:10.1016/j.physe.2007.08.093

barrier and finishes at the right end of the ith barrier), respectively. $\Theta_i(\mu_i^+) = 1$ if $\mu_i^+ > E_{1,i}^-$, and $\Theta_i(\mu_i^+) = 0$ if $\mu_i^+ < E_{1,i}^-$. The voltage bias condition is $\sum_{i=0}^N F_i l = V$ for the applied voltage V. We have denoted the spin-dependent subband energies ($\mathscr{E}$) (measured from the bottom of the ith well) by $E_{j,i}^{\pm} = E_j \mp \Delta_i/2$, with $\Delta_i = \Delta$ or 0, depending on whether the ith well contains magnetic impurities. N_D, ε, $-e$, $l = d + w$, and $-J_{i\to i+1}^{\pm}$ are the 2D doping density at the QWs, the average permittivity, the electron charge, the width of a MQWS period (d and w are barrier and well widths), and the tunneling current density across the ith barrier, respectively. Tunneling currents are calculated by the Transfer Hamiltonian method:

$$J_{i\to i+1}^{\pm} = \frac{ev^{(f)\pm}(F_i)}{l}\left\{n_i^{\pm} - \frac{m^* k_B T}{2\pi\hbar^2}\ln\left[1 + \mathrm{e}^{-eF_i l/k_B T}\times\left(\exp\left(\frac{2\pi\hbar^2 n_{i+1}^{\pm}}{m^* k_B T}\right) - 1\right)\right]\right\}, \quad i = 1,\ldots,N-1, \tag{3}$$

provided that scattering-induced broadening of energy levels is much smaller than sub-band energies and chemical potentials Ref. [3]. As boundary tunneling currents for $i = 0$ and N, we use (3) with $n_0^{\pm} = n_{N+1}^{\pm} = \kappa N_D/2$ (identical normal contacts with $\kappa \geqslant 1$) Ref. [1]. Initially, we set $F_i = V/[l(N+1)]$, $n_i^{\pm} = N_D/2$ (normal QWs). The spin-dependent "forward tunneling velocity" $v^{(f)\pm}$ is a sum of Lorentzians of width 2γ (the same value for all sub-bands, for simplicity) centered at the resonant field values $F_{j,i}^{\pm} = (E_{j,i+1}^{\pm} - E_{1,i}^{\pm})/(el)$, Ref. [3]:

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

Here $\mathscr{T}_i$ is proportional to the dimensionless transmission probability across the ith barrier and it can be found in Appendix A of Ref. [3].

3. Results

3.1. Self-sustained current oscillations

There are SSCOs for a variety of configurations, but only if one or more QWs contain magnetic impurities yielding a spin splitting sufficiently large. The nonmagnetic MQW structure does not exhibit SSCO. We consider a sample with $d = 10$ nm, $w = 5$ nm, $\tau_{sf} = 10^{-9}$ s (normal QW) and 10^{-11} s (magnetic QW), $m^* = 0.16m_0$, $\varepsilon = 7.1\varepsilon_0$, $T = 5$ K, $E_1 = 15.76$ meV, $E_2 = 61.99$ meV, $\gamma = 1$ meV, $\Delta = 15$ meV, $\kappa = 1$. Fig. 1 shows that if the only magnetic QW is the ith (with $1 \leqslant i < N-3$), the charge dipoles are emitted at this well, and dipole motion is limited to the last $N - i$ QWs.

3.2. Polarization

The spin polarization is defined as $P_i = (n_i^+ - n_i^-)/(n_i^+ + n_i^-)$. Let us consider a 4-well n-doped ZnSe/(Zn,Cd,Mn)Se weakly coupled MQWS with normal contacts and its first QW doped with magnetic impurities at 5 K. Fig. 2 shows the time evolution of the spin-polarized current densities, the electric field profile and the spin polarization at the different MQWS periods. We observe that the first and the second QWs remain highly polarized for most of the oscillation period (>80%) whereas the polarizations of the third and the fourth QWs are small <10%). Moreover, spin-up electrons yield the largest part of the total current through the structure.

3.3. Minimal doping density for self-oscillations

We have studied how doping density N_D affect the SSCOs. When the number of wells $N \geqslant 4$, the SSCOs appear if $N_D > N_{D,c}$. Fig. 3 shows our numerical results for different values of N. We have sought this first critical doping density for $4 \leqslant N \leqslant 50$ and found that the values of $N_{D,c}$ are fitted very well by the approximate formula

$$N_{D,c} = \frac{2}{N-2}\times 10^{10}\,\mathrm{cm}^{-2}, \tag{5}$$

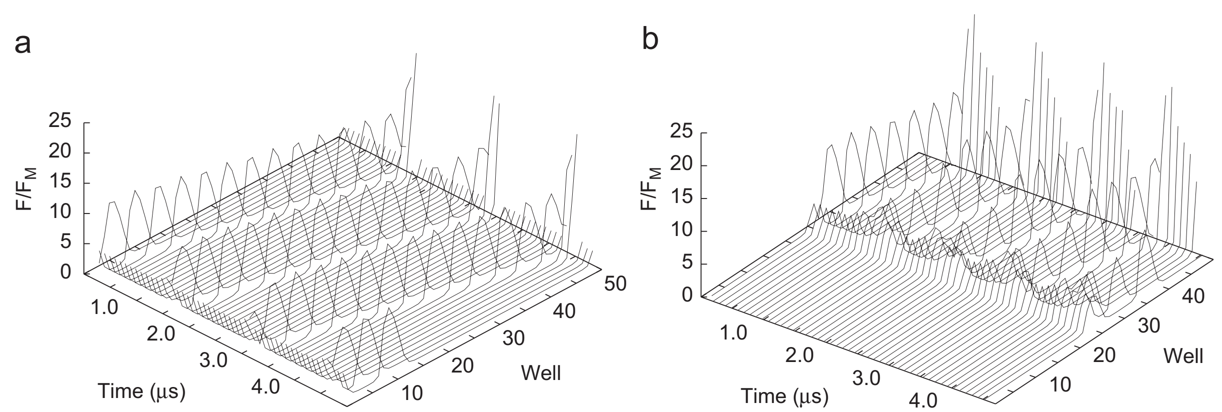

Fig. 1. Electric field profile vs QW index and time for $N = 50$, $V = 0.048$ V, $N_D = 10^{10}$ cm^{-2}, $F_M = 0.64$ kV/cm, $J_M = 0.409$ A/cm^2 if the magnetic QW is: (a) $i = 1$, (b) $i = 25$.

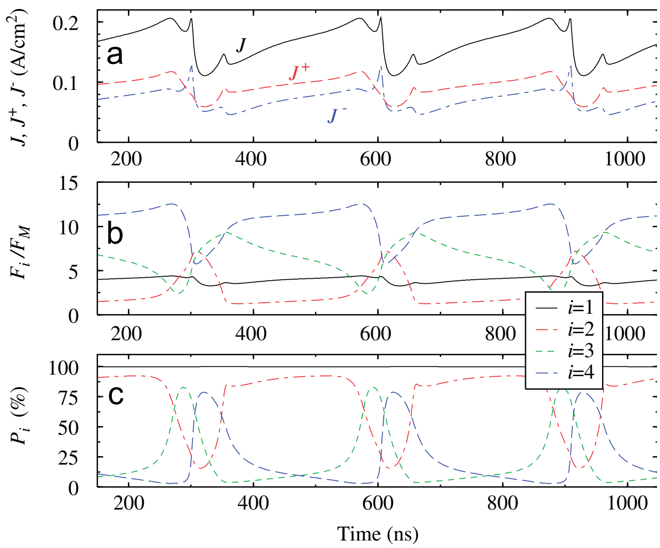

Fig. 2. (a) Tunneling current, (b) electric field, and (c) polarization, as a function of time during SSCOs at the i QW. Solid line ($i = 1$); dot-dashed ($i = 2$); dashed ($i = 3$); long dashed ($i = 4$).

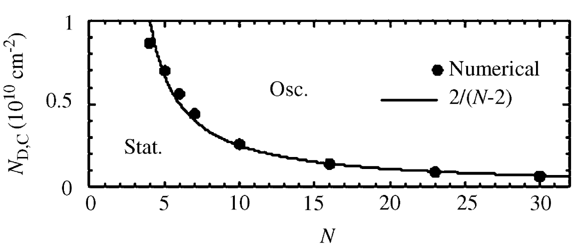

Fig. 3. Minimal doping density for SSCOs vs. N.

as N increases. It is important to observe that in the continuum limit as $N \to \infty$, this yields $NN_{D,c} \approx 2 \times 10^{10}\,\mathrm{cm}^{-2}$ which corresponds to the N–L criterion in the theory of the Gunn effect [4].

4. Concluding remarks

Our results could be used to construct an oscillatory spin polarized current injector. Current self-oscillations are due to periodic triggering of dipole waves at magnetized QWs. Other wells are fully polarized when the dipole wave is traversing them. Therefore a short device (with four wells) would periodically inject pulses of polarized current to the collector. 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 doping density needed to achieve spin polarized SSCOs. For self-oscillations to occur, a sufficient spin splitting should be induced by tailoring the magnetic impurity density and external magnetic fields.

Acknowledgments

Work financed by the Spanish Ministry of Education under grants MAT2005-05730-C02-01 (LLB & MC) and MAT2005-06444 (GP), by the MEC Ramón y Cajal program (RE) and by the EU Marie Curie Network: Project number 504574 (GP).

References

[1] D. Sánchez, A.H. MacDonald, G. Platero, Phys. Rev. B 65 (2001) 035301.
[2] M. Béjar, D. Sánchez, G. Platero, A.H. MacDonald, Phys. Rev. B 67 (2003) 045324.
[3] L.L. Bonilla, J. Phys.: Cond. Matter 14 (2002) 341.
[4] H. Kroemer, Proc. IEEE 52 (1964) 1736.