Proposal for a ferromagnetic multiwell spin oscillator

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The highly nonlinear coupling of transport and magnetic properties in a multiwell heterostructure, which comprises ferromagnetic quantum wells made of diluted magnetic semiconductors, is theoretically investigated. The interplay of resonant tunneling and carrier-mediated ferromagnetism in the magnetic wells induces very robust, self-sustained current and magnetization oscillations. Over a large window of steady bias voltages the spin polarization of the collector current is oscillating between positive and negative values, realizing a spin oscillator device. © 2010 American Institute of Physics. [doi:10.1063/1.3469999]

Magnetic resonant tunneling structures are prominent spintronic devices,1 which are proposed for spin valves, spin filtering,2–6 or for realizing digital magnetoresistance.7 In nonmagnetic multiwell heterostructures interesting dynamic effects such as the formation of electric field domains and the motion of charge dipoles through the structure can be observed.8,9 Recently, it has been predicted that in structures with paramagnetic wells these phenomena can be controlled by an external magnetic field.10,11 The paramagnetic systems can behave as a spin oscillator device, in which moving charge dipoles generate spin-polarized current oscillations in the megahertz range.11,12 In ferromagnetic multiwell structures made of dilute magnetic semiconductors (DMSs) also the magnetic order will become dynamic.13 This additional degree of freedom enriches the dynamic complexity, which up to now is still largely unexplored. DMSs (Refs. 14–16) are made magnetic by doping them with transition metal elements, e.g., by incorporating Mn in a GaAs crystal host. In several experiments ferromagnetism has been generated in the bulk by tailoring the actual particle density electrically or optically.17,18 In two-dimensional confined systems made of DMSs the magnetic order depends strongly on the local spin density, which is influenced by the tunneling current.19,20 While in paramagnetic systems self-sustained oscillations occur due to the formation of moving charge dipoles, the underlying mechanism for the current fluctuations in ferromagnetic structures turns out to be based on the inversion of the spin population in adjacent wells.

In this article a detailed study of the dynamics in a ferromagnetic four-well system, as a prototype of the expected multiwell functionality, is provided. The carrier dynamics is described by a self-consistent sequential tunneling model which includes momentum and spin relaxation inside the wells. The feedback effects of both the carriers Coulomb interaction and the magnetic exchange coupling with the magnetic ions are described within a mean-field picture. We give a qualitative explanation for the occurrence of spin-polarized current oscillations, which realizes the functionality of a spin oscillator device.

The band profile of a four-well heterostructure with two ferromagnetic quantum wells made of a DMS, e.g., of GaMnAs, is sketched in Fig. 1. In the ferromagnetic wells the ferromagnetic order of the magnetic ions is mediated by the itinerant carriers. Describing the mutual exchange interaction within a mean-field picture allows to derive an analytic expression for the exchange splitting $\Delta^0$ of the subbands in the ferromagnetic wells:19–21

$$\Delta^0 = J_{pd} \int dz n_{imp}(z)|\psi_0(z)|^2 \times \frac{SB_z\left[\frac{SJ_{pd}(n_i^0 - n_i^\downarrow)|\psi_0(z)|^2}{k_BT}\right]}{S_{p}(n_i^\uparrow - n_i^\downarrow)|\psi_0(z)|^2},$$

where $J_{pd}$ is the coupling strength between the impurity spin and the carrier spin density (in case of GaMnAs p-like holes couple to the d-like impurity electrons), $z$ is the longitudinal (growth) direction of the structure, $n_{imp}(z)$ is the impurity density profile of magnetically active ions, $\psi_0(z)$ labels the well ground wave function, $s = 1/2$ is the particles spin, $k_B$ denotes Boltzmanns constant, and $T$ is the lattice temperature. The Brillouin function of order $S$ is denoted by $B_S$, where $S$ is the impurity spin, which for Mn equals 5/2. We assume a homogenous impurity distribution making the spin polarization $\xi_i = s(n_i^\uparrow - n_i^\downarrow)$ the determining factor for the exchange splitting $\Delta^0$.

The well spin polarization can be rapidly changed by in- and out-tunneling particles. However, the magnetic impuri-

![FIG. 1. (Color online) Schematic scheme of the band profile of the ferromagnetic four-well structure. The exchange interaction of the magnetic ions in the second and third well is mediated by the carriers tunneling in and out of the wells.](image-url)
ties need some time to respond until the corresponding mean field value $\Delta^\prime$ is established. In the case of GaMnAs, experimental studies of the magnetization dynamics revealed typical response times $\tau_s$ of about 100 ps. We model the magnetization evolution in the ferromagnetic wells $i= (2, 3)$ within the relaxation time approximation, $d\Delta_i/dt = - (\Delta_i - \Delta_i^0)/\tau_s$.

The transport through weakly coupled multiwell structures is well described by a sequential tunneling model, which is presented in detail in Refs. 9 and 11. The transport model includes the following assumptions: (i) The wells are weakly coupled and tunneling can be described by a transfer Hamiltonian formalism. (ii) The particles in each well always stay in a quasiequilibrium state $f(\varepsilon - \mu^0_i) = \{\exp[(\varepsilon - \mu^0_i)/k_BT] + 1\}^{-1}$, $(\sigma = \uparrow, \downarrow = \pm 1/2)$ due to elastic and inelastic scattering, which is assumed to constitute the shortest time scale in the problem ($\tau_{\text{scat}} = 1$ ps). The chemical potential $\mu^0_i$ is related to the particle density via $n_i^0 = m^*k_BT/2\hbar^2 \ln[1 + \exp(\mu^0_i - \varepsilon_i^0)/k_BT]$ with $m^*$ being the effective mass, and $\varepsilon_i^0$ denotes the spin-dependent ground level energy in the $i$th well. (iii) Particles in the first excited subband relax rapidly to the ground level by inelastic scattering processes, e.g., due to emission of LO-phonons. This happens within a few picoseconds, which is much smaller than the other relevant time scales occurring in the problem. (iv) The spectral function $A_s^0(\varepsilon)$ of the subbands is a Lorentzian with the broadening given by $\gamma = \hbar/2\tau_{\text{scat}}$. (v) During tunneling processes the parallel momentum and spin are conserved, i.e., effects of interface roughness are not taken into account. (vi) Spin flipping processes can be described by a single spin relaxation time $\tau_s$. Based on these approximations rate equations for the spin-dependent particle densities can be found

$$\frac{dn_i^\sigma}{dt} = J_{i-\rightarrow i-1}^\sigma(F_{i-1}) - J_{i-\rightarrow i+1}^\sigma(F_i) = \frac{n_i^\sigma - n_i^{0,\sigma}}{\tau_s}, \quad i = 2, 3.$$ (2)

The quasiequilibrium particle spin densities $n_i^{0,\sigma}$ are calculated from the two conditions $n_i^\uparrow + n_i^\downarrow = n_i^0 + n_i^{0,\downarrow}$ and $n_i^0 = n_i^{0,\uparrow} = \xi_i^0/s$, with $\xi_i^0$ resulting from inverting Eq. (1) for the actual $\Delta_i$. The tunneling currents $J_{i-\rightarrow i+1}^\sigma$ depend on the electric field $F_i$ at the $i$th barrier and can be derived microscopically within the Kubo-formalism, yielding the general expression

$$J_{i-\rightarrow i+1}^\sigma = -\frac{e}{2\pi\hbar} \sum_{k, \xi_{i+1}} T_{k, \xi_{i+1}} \int \frac{d\varepsilon A_{k, \xi_{i+1}}^\sigma A_{k, \xi_{i+1}}^\sigma(e + \varepsilon \phi)}{(e - \mu_i^0) - f(e - \mu_i^0 + e + \varepsilon \phi)}, \quad i = 2, 3.$$ (3)

with $\phi$ being the elementary charge, $T_{k, \xi_{i+1}}$ denotes the transmission coefficient between particular wave vector states of adjacent wells, and $e \phi_i$ is the voltage drop across the $i$th barrier. The electron-electron interaction is taken into account within a discretized Poisson equation $F_i - F_{i-1} = e(n_i^\uparrow + n_i^\downarrow - N_{\text{back}})/e$ with $\varepsilon$ denoting the dielectric constant and $N_{\text{back}}$ the background charge.

The tunneling currents are strongly sensitive to the relative alignment of adjacent subbands and since the quantum well levels $\varepsilon_i^{0,\sigma} = \varepsilon_i + \phi_i - \sigma \Delta_i$ explicitly depend on the magnetic exchange splitting and the electrostatic potential $\phi_i$ all equations are coupled highly nonlinearly. A self-consistent solution of the system of differential equations is found by assuming that the voltage drops linearly through the structure at time $t=0$ and by propagating in time until a converged solution is reached.

For the numerical simulations we used generic parameters representing GaAs and GaMnAs quantum wells, respectively, $T=4.2$ K, $m^* = 0.5m_0$, $\varepsilon_i = 12.9$, $V_{\text{bar}} = 300$ meV, $d = 20$ Å, $w = 20$ Å, $\varepsilon_i = 80$ meV, $\varepsilon_i = 188$ meV, $\mu_e = 100$ meV, $n_{\text{imp}} = 0.5 \times 10^{20}$ cm$^{-3}$, $J_{\text{p}} = 0.15$ eV nm$^{-1}$, $\gamma = 2$ meV, and $\tau_s = 0.1$ ns, where $m_0$ denotes the free electron mass, $\varepsilon_i$ is the relative permittivity, $V_{\text{bar}}$ is the barrier height, $d$ and $w$ are the barrier and quantum well widths, $\varepsilon_i$ and $\varepsilon_i$ are the energies of the two lowest subbands, and $\mu_e$ is the emitter Fermi energy. Due to various lattice defects, e.g., Mn interstitial or antisite defects, MnGaAs is a heavily compensated system such that the background charge $N_{\text{back}} = 0.1 n_{\text{imp}} W = 10^{12}$ cm$^{-2}$ is typically only of about 10% of the nominal Mn doping density. The boundary currents $J_{0-1}$ and $J_{N-N+1}$ with $N$ denoting the total number of quantum wells are determined by the tunneling from or into a three-dimensional Fermi sea at the emitter and collector side, respectively.

Figure 2 shows the current-voltage ($I$-$V$) characteristics of the four well structure. Self-sustained current oscillations appear in the voltage range of $V = 0.22-0.42$ V, in which both the maximum and minimum values of the oscillations are indicated by the solid and dashed lines, respectively. The inset shows the spin polarization of the collector current vs applied bias $V$ in the voltage range in which oscillations are occurring.

By analyzing the local spin densities and the flowing tunneling currents in-between adjacent wells a qualitative understanding for the underlying mechanism of these oscillations can be found: (i) In the bias region, in which self-oscillating processes dominate, spin relaxation times are longer than the characteristic voltage change timescale, a condition for self-sustained oscillations at the collector.

![Image](https://example.com/image.png) # FIG. 2. ($I$-$V$)-characteristics of the four well structure. Self-sustained current oscillations appear in the voltage range of $V = 0.22-0.42$ V, in which both the maximum and minimum values of the oscillations are indicated by the solid and dashed lines, respectively. The inset shows the spin polarization of the collector current vs applied bias $V$ in the voltage range in which oscillations are occurring.
sustained oscillations are occurring, the currents $J_{1\rightarrow 2}$ and $J_{2\rightarrow 3}$ are governed by tunneling from the ground state to the first excited subband of the neighboring wells, as shown schematically in Fig. 1. (ii) According to an initial small positive energy splitting, spin up particles accumulate in the second well and, hence, $\Delta_2$ increases. (iii) During this accumulation, particles start to tunnel to the third well. At some point the spin extraction to the third well overwhelms the spin injection from the first well. Therefore, with time the spin up particles in the second well are completely extracted and spin down particles become the majority species therein. This spin inversion comes along with an inversion of the exchange splitting $\Delta_2 \propto (n_1 - n_1)$ from positive to negative values. (iv) Now the whole process starts from the beginning with the role of spin up and spin down particles being interchanged.

The frequency of the oscillations is of the order of about 0.25 GHz and is determined by how fast spin can be accumulated in a well and afterwards extracted to the adjacent well. This process of spin inversion depends on all relevant time scales occurring in the problem, i.e., the particle tunneling time $\tau_s$, the spin relaxation time $\tau_s$, and the response time of the Mn-ions $\tau_3$.

In summary, we have shown that in ferromagnetic multiwell structures an interesting dynamic interplay of resonant tunneling and carrier mediated ferromagnetism emerges, which results in stable self-sustained current oscillations. The underlying mechanism based on spin inversion is completely different from the one in paramagnetic multiwell structures, in which moving charge dipoles are formed. The ferromagnetic heterostructure may be useful as a spin oscillator device.

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1. J. Fabian, A. Matos-Abiague, C. Ertler, P. Stano, and I. Žutić, Acta Physica Slovaca 57, 565 (2007).
2. E. Likovitch, K. Russell, W. Yi, V. Narayananurthi, K.-C. Ku, M. Zhu, and N. Samarth, Phys. Rev. B 80, 201307(R) (2009).
3. A. Slobodskyy, C. Gould, T. Slobodskyy, C. R. Becker, G. Schmidt, and D. O. Demchenko, Phys. Rev. Lett. 90, 246601 (2003).
4. A. G. Petukhov, A. N. Chantis, and D. O. Demchenko, Phys. Rev. Lett. 89, 107205 (2002).
5. S. Ohya, P. N. Hai, Y. Mizuno, and M. Tanaka, Phys. Rev. B 75, 155328 (2007).
6. C. Ertler and J. Fabian, Appl. Phys. Lett. 89, 242101 (2006).
7. C. Ertler and J. Fabian, Phys. Rev. B 75, 195323 (2007).
8. L. L. Bonilla and H. T. Grahn, Rep. Prog. Phys. 68, 577 (2005).
9. L. L. Bonilla, R. Escobedo, and G. D. Acqua, Phys. Rev. B 73, 115341 (2006).
10. D. Sánchez, A. H. MacDonald, and G. Platero, Phys. Rev. B 65, 035301 (2001).
11. R. Escobedo, M. Carretero, L. L. Bonilla, and G. Platero, Phys. Rev. B 80, 155202 (2009).
12. L. L. Bonilla, R. Escobedo, M. Carretero, and G. Platero, Appl. Phys. Lett. 91, 092102 (2007).
13. C. Ertler and J. Fabian, Phys. Rev. Lett. 101, 077202 (2008).
14. H. Ohno, Science 281, 951 (1998).
15. T. Dietl, in Modern Aspects of Spin Physics, edited by W. Pötz, J. Fabian, and U. Hohenester (Springer, New York, 2007), pp. 1–46.
16. T. Jungwirth, J. Sinova, J. Mašek, J. Kucera, and A. H. MacDonald, Rev. Mod. Phys. 78, 809 (2006).
17. H. Ohno, D. Chiba, F. Matsukura, T. O. E. Abe, T. Dietl, Y. Ohno, and K. Ohtani, Nature (London) 408, 944 (2000).
18. H. Boukari, P. Kossacki, M. Bertolini, D. Ferrand, J. Cibert, S. Tatarenko, A. Wasieła, J. A. Gaj, and T. Dietl, Phys. Rev. Lett. 88, 207204 (2002).
19. T. Dietl, A. Haury, and Y. M. d’Aubigné, Phys. Rev. B 55, R3347 (1997).
20. T. Jungwirth, W. A. Atkinson, B. H. Lee, and A. H. MacDonald, Phys. Rev. B 59, 9818 (1999).
21. B. Lee, T. Jungwirth, and A. H. MacDonald, Phys. Rev. B 61, 15606 (2000).
22. J. Wang, I. Cotoros, K. M. Dani, X. Liu, J. K. Furdyna, and D. S. Chemla, Phys. Rev. Lett. 98, 217401 (2007).
23. H. Xu and S. W. Teitsworth, Phys. Rev. B 76, 235302 (2007).
24. B. Baylac, T. Amand, X. Marie, B. bareys, M. Brousseau, G. Bacquet, and V. Thierry-Mieg, Solid State Commun. 93, 57 (1995).
25. S. Das Sarma, E. H. Hwang, and A. Kaminski, Phys. Rev. B 67, 155201 (2003).