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Abstract

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Reference


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Spin-polarized current oscillations in diluted magnetic semiconductor multiple quantum wells

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We study the spin and charge dynamics of electrons in n-doped II-VI semiconductor multiple quantum wells when one or more quantum wells are doped with Mn. The interplay between strongly nonlinear interwell charge transport and the large tunable spin splitting induced by exchange interactions with spin-polarized Mn ions produces interesting spin-dependent features. The tunneling current between quantum wells can be strongly spin polarized and, under certain conditions, can develop self-sustained oscillations under a finite dc voltage. The spin polarization oscillates in both magnetic and nonmagnetic quantum wells and the time average in magnetic wells can differ from its zero-voltage value. Our numerical simulations demonstrate that the amplitude of the spin-polarization oscillations depends on the distribution of magnetic wells within the sample. We discuss how the spin-polarized current and the spin polarization of the quantum wells can be tailored experimentally.

I. INTRODUCTION

Current information technology devices are based on the manipulation of electrical charge flow using electric fields. Recent technological developments that exploit magnetotransport effects in ferromagnetic metals have increased interest in exploring other ideas. Effects based on the electron spin degree of freedom can be used either to improve device functionality, or to create radically new devices that either implement new processing algorithms, as in quantum computing, or that are based on different physical principles, as in spin field-effect transistors. The extreme sensitivity to external magnetic fields that has been exploited in ferromagnetic metals is ultimately a consequence of the collective behavior of many electronic spins that follows from long-range ferromagnetic order. Ferromagnetic semiconductors are important because their magnetic properties can in principle be engineered by doping or by adjusting gate voltages. Considerable progress has been recently made in manipulating the ferromagnetism that occurs in a number of common III-V compound semiconductors when they are doped with the magnetic element Mn. Although they are not normally ferromagnetic, II-VI semiconductors doped with Mn also respond strongly to external magnetic fields and have properties that are similar in many respects. The transport properties of Mn-based heterostructures have been studied including miniband transport in strongly coupled superlattices doped with Mn.

In a recent paper three of us analyzed the nonlinear transport properties of II-VI semiconductors with weakly coupled highly n-doped quantum wells in which one or more of the quantum wells is doped with Mn. The interplay between electronic spin, charge accumulation, and resonant interwell tunneling effects that takes place in these systems has been shown to alter the formation of stable electric-field domains and to produce hysteretic behavior in both spin and charge distributions. Spin polarization is induced in both magnetic and nonmagnetic quantum wells when driven by strong dc electric fields.

In nonmagnetic highly n-doped semiconductor weakly coupled multiple quantum wells, it is well known that dc electrical transport is dominated by the formation of electric-field domains. This effect is reflected in the nonlinear current-voltage characteristics which present a sawtooth structure that arises from the interplay between electron-electron interactions and resonant intersubband tunneling between neighboring quantum wells. When the carrier density is below a critical value, however, the formation of electric-field domains is not stable and the nonlinear transport properties change drastically in comparison with the highly n-doped systems. Intermediate n-doped systems have very rich behavior. The time-averaged current-voltage characteristics presents flat plateaus. Real-time measurements show that within a plateau the current has an undamped oscillatory dependence on time. These self-sustained electron current oscillations come from the dynamics of the domain wall separating electric-field domains and persist even at room temperature, making these devices promising candidates for microwave generation with frequencies that extend from kHz to GHz.

In this paper we explore interesting features that occur in weakly coupled quantum wells that support self-sustained oscillations when they are doped with magnetic impurities. In Sec. II we briefly review the model that we use for incoherent transport between quantum wells which can contain magnetic impurities. In Sec. III we summarize and discuss the results we have obtained by solving this model numerically for some representative circumstances. Finally, in Sec. IV we present our conclusions.

II. MODEL

Our theory of transport through diluted magnetic semiconductor multiple quantum wells is built on (i) a theory for the tunneling current between two spin-polarized two-
dimensional electron gases (2DEG’s); (ii) a continuity equation that accounts for relaxation of nonequilibrium spin populations; (iii) a relationship between the up and down chemical potentials and their densities; (iv) a mean-field theory for the interaction between 2DEG electrons and Mn spins; and (v) an expression to take into account the Coulomb interaction between charge accumulations in the quantum wells.

In weakly coupled multiple quantum wells, it is a good approximation to treat tunnelling of quasiparticles between neighboring quantum wells by leading-order perturbation theory. We ignore interwell spin-flip processes, so that currents are carried between wells by the two spin subsystems in parallel. Accordingly, the current per spin $\sigma$ from the $i$th well to the $(i+1)$st well, $J_{i,i+1}^\sigma$, can be properly described by a transfer Hamiltonian model$^{14,17}$ with a Lorentzian lifetime within each well:$^{22}$

$$\frac{dn_i^\sigma}{dt} = -\frac{n_i^\sigma}{\tau_{sf}} + \frac{\mu_i^\sigma - E_{i,1}^\sigma}{\tau_{sf}} v_0,$$

(2)

$$\frac{dn_i^\bar{\sigma}}{dt} = -\frac{n_i^\bar{\sigma}}{\tau_{sf}} + \frac{\mu_i^\bar{\sigma} - E_{i,1}^\bar{\sigma}}{\tau_{sf}} v_0.$$

(3)

For large enough $\Delta$, Eq. (2) leads to an equilibrium state with full spin polarization. The continuity equations that describe the time evolution of the partial densities in each quantum well include both spin-relaxation and transport currents:

$$\frac{dn_i^\sigma}{dt} = \frac{J_{i-1,i}^\sigma}{e} - \frac{J_{i+1,i}^\sigma}{e} - \frac{\mu_i^\sigma - \mu_i^\bar{\sigma}}{\tau_{sf}} v_0 \quad i = 1, \ldots, N$$

(4)

for the case $\mu_i^\sigma - E_{i,1}^\sigma > \Delta$ ($N$ is the number of quantum wells). Otherwise, Eqs. (2) and (3) must replace the second term on the right-hand side of Eq. (4).

III. RESULTS

In order to obtain electric-field domain physics it is necessary to account for electron-electron interactions among conduction-band electrons at the mean-field level by solving the Poisson equation.$^{12}$ Including a displacement current contribution, the total current density $J(t)$ traversing the sample at time $t$ is $J(t) = (e/d)(dV/dt) + J_{i,i+1}(t)$ which is independent of $i$ and where $J_{i,i+1}(t) = J_{i,i+1}^\uparrow(t) + J_{i,i+1}^\downarrow(t)$. $e$ is the sample permittivity, $d$ is the multiple quantum well period, and $V_i$ the voltage drop between wells $i$ and $i+1$. We model a $N=50$ n-doped ZnSe/Zn$_{0.8}$Cd$_{0.2}$Se quantum well system$^6$ with well and barrier widths of 10 and 5 nm, respectively. Mn impurities are placed in the 1st and 50th quantum wells. We have chosen the spin-relaxation time within the magnetic and nonmagnetic quantum wells to be $\tau_{sd}=10^{-11}$ s and $\tau_{sd}=10^{-9}$ s, respectively. The quantum wells and the contacts are $n$ doped with $N_w$ and $N_c = \kappa N_w$, respectively. We take $\kappa=1.1$. Figure 1 shows the $J$-$V$ characteristics for (a) $N_w=1\times10^{12}$ cm$^{-2}$ and (b) $N_w=9 \times10^{10}$ cm$^{-2}$. The spin splitting is $\Delta=2$ meV in both cases. With these parameters, the magnetic quantum wells (if taken as isolated) are partially polarized: $P=7\%$ [case (a)] and $P=75\%$ [case (b)], where $P_i=(n_i^\uparrow-n_i^\downarrow)/n_i$ is the spin polarization of the $i$th well. As expected, Fig. 1(a) exhibits a series of sharp discontinuities in the negative differential conductance region which are linked to the formation of static electric-field domains. Along each branch, charge accumulates at the domain wall, forming a monopole that jumps discretely toward the emitter as $V$ increases. When $N_w$ is lowered [see Fig. 1(b)], the branches are substituted by a plateau on which current oscillates periodically with time. We observe undamped self-oscillations of the current in the range $V=0.2\rightarrow 1.5$ V.

In Fig. 2 we plot the total current (a), and the spin-up (b) and spin-down (c) currents toward the collector as a function of time for $V=0.5$ V for the sample described in Fig. 1(b), i.e., for an intermediated $n$-doped sample: $N_w=9\times10^{10}$ and $N_c=9.9\times10^{10}$ which presents self-sustained oscillations in the absence of magnetic quantum wells. The current oscilla-
charge doping, the domain walls lead to traveling dipoles described and experimentally observed. Lowering the contact dynamics of the monopole has been theoretically described over one or two quantum wells. In nonmagnetic multiple quantum wells, monopole and dipole domain walls can coexist at a fixed dc bias under certain conditions.

In Fig. 3(a) we plot the charge-density quantum well distribution at the times $t_1$-$t_5$ marked in Fig. 2. We observe that for the case illustrated the domain wall is a monopole which travels through only a part of the structure. In Fig. 3(b) the charge density at times $t_5$-$t_{10}$ is presented. These plots illustrate an interesting feature of our results: the domain wall is now a dipole with both charge accumulation and depletion. During each oscillation period the domain wall undergoes a transition from a monopole to a dipole one and back. An exciting consequence of this behavior is shown in Fig. 4 where the polarization in the magnetic quantum well is plotted as a function of $t$. We observe that the polarization reaches three different values during one oscillation: during the intervals of dipole propagation the polarization abruptly drops and increases up to a practically fully polarization configuration. When the domain wall becomes a monopole the polarization remains practically constant up to the time where the dipole is formed. The constant value of the polarization is close to the value of the polarization of the isolated quantum well.

The previous observation can be explained by looking at how the spin polarization in the Mn-doped quantum well influences the tunneling probability to neighboring wells and by the strongly nonlinear transport in the negative differential conductance region. The chemical potentials for spin-up and -down electrons within a magnetic quantum well ($\mu_\uparrow$ and $\mu_\downarrow$, respectively) do not take on the same value in the stationary limit as they would do in an isolated quantum well because of the finite spin-flip and tunneling rates and because self-consistency changes the charge density in the quantum wells ($n_m$).
The magnetic quantum well spin polarization in the non-equilibrium case may be related to the instantaneous local chemical potentials for majority and minority spins:

\[ P = \frac{v_0 \Delta}{n_m} + \frac{\delta \mu_m v_0}{n_m}, \]

where \( \delta \mu_m = \mu_m^1 - \mu_m^0 \). This expression is obtained assuming the linear noninteracting 2DEG relationship between density and chemical potential, so that correlation effects are not included: \( n_i^0 = v_0 (\mu_i^0 - E_i^0) \). The above expression for the polarization \( P \) is also valid for nonmagnetic quantum wells. In this case, the spin splitting is very small and it is basically the second term of Eq. (5) that is responsible for the induced finite polarization.

As we can see from Eq. (5), increasing the density reduces the relative polarization. It follows that a monopole domain wall accumulation layer in the magnetic well will reduce \( P \) compared to the equilibrium case. This reduction was observed for multiple quantum wells with stable electric-field domains and stationary currents. In contrast, in the self-sustained current oscillations the magnetic well polarization can increase with respect to the isolated case, even reaching full spin-polarization. Comparing Figs. 3 and 4, we note that the high polarization configuration state occurs at \( t = t_0 \), when the front wave is a dipole with one depletion and one accumulation layer (domain walls) and the depletion region is located at the magnetically doped quantum well. The large polarization occurs in part because of the local instantaneous decrease in the total density of electrons in the magnetic well. The frequency, amplitude, and shape of the current oscillations depend on the dynamics of the polarized charge, which itself depends on the distribution of magnetic quantum wells in the sample. Then tailoring the sample configuration should enable control of not only the frequency and amplitude of the current oscillations, but also of the spin polarization and its time dependence. To illustrate this we present in Fig. 5 results for the case in which two magnetic quantum wells are placed in the system, one adjacent to the emitter and another at a variable position. We observe that when the magnetic quantum well is close to the position of the domain wall the amplitude of the polarization oscillations increases [Fig. 5(d)]. Because the polarization depends on the inverse of the charge density, whenever the domain wall enters and leaves the magnetic quantum well, the amplitude of the magnetization oscillations increases and \( P \) oscillates between 20% and 100%. As the magnetic quantum well comes closer to the collector, the polarization exhibits two flat regions within an oscillation. Since the period of these electric-field domain oscillations is of the order of 5 \( \mu s \), time resolved measurements of PL in illuminated multiple quantum well samples should allow this polarization change to be observable.

IV. CONCLUSION

In closing, we have studied the spin dynamics in multiple quantum well systems doped with magnetic impurities. We predict time-dependent periodic oscillations of the spin-polarized current and of the spin polarization in both magnetic and nonmagnetic quantum wells. The interplay between nonlinearity of the current-voltage relationship and the exchange interaction produces interesting spin-dependent features which are sensitive to spin relaxation times and to the equilibrium exchange fields in the quantum wells which can be tailored by adjusting external field and temperature. These spin-dependent features can potentially be exploited for device applications. In particular, our results for the oscillating spin-polarized currents at the collector suggest that these systems could be designed as spin-polarized current injection oscillators.
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