Intersubband dynamics of spin polarized carriers

M Vogel\textsuperscript{1}, A Vagov\textsuperscript{1}, V M Axt\textsuperscript{1}, A Seilmeier\textsuperscript{2} and T Kuhn\textsuperscript{3}

\textsuperscript{1} Institute for Theoretical Physics III, University of Bayreuth, 95440 Bayreuth, GERMANY,
\textsuperscript{2} Institute for Experimental Physics III, University of Bayreuth, 95440 Bayreuth, GERMANY,
\textsuperscript{3} Institute for Solid State Theory, University of Münster, 48149 Münster, GERMANY.

E-mail: martin.axt@uni-bayreuth.de

Abstract. The intersubband (ISB) dynamics of spin orientated carriers generated in undoped quantum wells by circularly polarized interband excitations is analyzed theoretically. It is shown that short THz pulses in resonance with the lowest conduction ISB transition can be used to switch the spin orientation in a given subband without changing the total subband occupation. For longer ISB pulses a periodic modulation of the spin orientation is found. However, when the Coulomb interaction is taken into account the total subband density is typically also modulated which differs from expectations based on calculations in a three band model of non-interacting particles. The dependence on the ratio of the subband masses is discussed as well as the observability of these effects in pump-probe type measurements.

1. Introduction

It is a central goal of spintronic devices to manipulate spin and charge degrees of freedom independently. Intersubband (ISB) transitions in quantum wells are not usually discussed in this connection, because in the most common set-ups that test ISB transitions no preferred spin direction is initially prepared and the subsequent laser induced dynamics is typically insensitive to spins. This is because the dominant coupling is to the allowed dipole transitions oriented linearly in growth direction which is not spin selective. Circularly polarized in-plane laser fields couple to ISB transitions only via mechanisms that are typically about three orders of magnitude weaker than the dominant dipole coupling and thus the resulting spin-orientation effects are rather weak [1]. In the present paper we use a combination of interband (IB) and ISB excitations where only the dominant dipole couplings are considered. Circularly polarized laser pulses in resonance with the IB transitions are used to prepare a distribution of spin polarized carriers in the conduction subbands (CSB). The main focus of the paper is the spin dependent ISB dynamics that follows this preparation step.

To be specific, we consider the excitation conditions that are depicted schematically in Fig. 1. First, a $\sigma^+$-polarized IB-pulse in resonance with the transition between the energetically highest heavy-hole type valence subband and the lowest CSB generates an electron-hole pair where the electron is, according to the usual selection rules, spin-down-polarized. Then a linearly polarized ISB pulse performs a Rabi rotation and thus promotes the spin-down electrons to the second CSB. A second IB-pulse, this time $\sigma^-$-polarized, is used to create a population of spin-up electrons in the lowest CSB. This protocol leads to a time evolution through the states (a)-(d) illustrated in the upper part of Fig. 1. The goal of this protocol is to prepare equal occupations of the two lowest CSBs with opposite spins. Once this is achieved the ISB dynamics induced...
Figure 1. Top: preparation and manipulation scheme; Middle: pulse sequence. Bottom: occupation of the lowest conduction subband. The symbol $\uparrow$ (↓) specifies the density with spin up (down) while $\uparrow + \downarrow$ marks the total subband density. The quantization axis for the spin is the $z$-direction, i.e. the growth direction. Parameters: conduction subband masses $m_{c1} = 0.068m_0, m_{c2} = 0.071m_0, m_0 = $ free electron mass, decoherence times $T_{IB} = 1$ ps, $T_{ISB} = 3$ ps, well width $d = 25$ nm, separation of conduction subbands $\Delta E_C = E_{c2} - E_{c1} = 25$ meV.

2. Numerical results

We have simulated the above sketched scenario within a $k$-space density matrix approach where in addition to the band energies the Coulomb interaction is accounted for on the mean-field level [2]. We have modeled a 25 nm wide quantum well with infinitely high barriers using standard GaAs parameters. The separation of the lowest CSBs evaluates for this structure to $\Delta E_C = 25$ meV, i.e., $\Delta E_C$ is considerably lower than the energy of longitudinal optical phonons of $E_{LO} = 36$ meV. In this case ISB scattering times above 100 ps up to several hundred ps are common at low temperatures [3]. Thus, ISB relaxation can be neglected on the short time scales studied here. Electron spin relaxation times may even reach nanoseconds [4] and are disregarded as well. Hole spin relaxation times may be short (of the order of a few ps) but these processes have only a marginal influence on the ISB dynamics. Corresponding simulations (not shown) revealed that they have some effect on the preparation stages [cf. Fig. 1 (a)-(d)] which involve IB transitions. These effects can, however, easily be compensated by suitably adjusting the intensities of the IB pulses [5] with the result that with or without accounting for hole spin relaxation practically the same final states in the CSBs can be prepared. For simplicity we show here results calculated without hole relaxation. We account, however, for decoherence times of $T_{IB} = 1$ ps for IB and $T_{ISB} = 3$ ps for ISB transitions.

Plotted in the lower part of Fig. 1 are calculated occupations of the lowest CSB. Apart from the total occupation ($\uparrow + \downarrow$, solid) also the occupations of spin-down ($\downarrow$, dotted) and spin-up ($\uparrow$, dashed) states are shown. The middle part of the figure illustrates the pulse sequence. We have considered IB pulses of 300 fs duration Full-Width-at-Half-Maximum (FWHM) of the intensity which guarantees a selective excitation of only the lowest subband. The duration of ISB-pulses has been adjusted to 160 fs which for a pulse of central frequency $\hbar \omega = 25$ meV
of has been used to drive the $x_{Sq}$ dynamics. Part $P_{R}$ is calculated with a ratio of the $r_{Sq}$ masses to switch the spin expectation value in a given subband essentially without changing the total spin orientation of the carriers in the lowest $r_{Sq}$. It turns out that it is indeed possible to decide also experimentally whether spin manipulations are di ff erent for carriers in di ff erent subbands [h]. The amplitude of the modulation of the total subband occupation is, however, accompanied by a similar modulation of the resonant and energies caused by roulomb interactions resulting in Rabi rotations that are o ff ected by the mass ratio and, for the standard $m_{c2}/m_{c1} = 1.04$, practically no modulation is seen [Fig. 2 (d)]. Also note that for the same pulse intensities simulations with roulomb interaction yield higher electron densities due to the Coulomb enhancement in the absorption process.

Fig. 2 shows results where after the preparation phase a single $6\pi$ ISB pulse of 2 ps duration has been used to drive the ISB dynamics. Part (a) is calculated with a ratio of the CSB masses of $m_{c2}/m_{c1} = 1.04$ which is a typical value for this separation of subband energies [8] and which has also been used in Fig. 1. We observe a periodic modulation of the spin occupation in the lowest subband. This modulation is, however, accompanied by a similar modulation of the total subband occupation. This is mainly due to renormalizations of the ISB transition energies caused by Coulomb interactions resulting in Rabi rotations that are off-resonant and thus incomplete. Even for initially equal occupations of the two subbands the number of carriers rotated down does not equal the number of carriers rotated up because the renormalizations are different for carriers in different subbands [9]. The amplitude of the modulation of the total subband occupation turns out to be strongly dependent on the CSB mass ratio. Interestingly, the weakest modulation is not found for equal masses [Fig. 2 (b)] but for a slightly lower value of $m_{c2}/m_{c1} = 0.97$ [Fig. 2 (c)] for which the effect is indeed rather weak. It should also be noted that this behavior is not expected in a model where the Coulomb interaction is neglected. Here, the total subband density is only marginally affected by the mass ratio and, for the standard value of $m_{c2}/m_{c1} = 1.04$, practically no modulation is seen [Fig. 2 (d)].

It is important that it is possible to decide also experimentally whether spin manipulations have been successfully performed independent from charge manipulations. A standard way to monitor spin-dependent occupations is to compare the absorption of circularly and linearly polarized $IB$ pulses. These signals should reflect the spin dependent densities because of the

![Figure 2](image_url)
spin dependence of blocking effects. Shown in Fig. 3 is the absorption of weak 300 fs IB test pulses of different polarizations: linear $x$ (solid), circular $\sigma^-$ (dotted) and circular $\sigma^+$ (dashed). The simulations have been performed for the excitation conditions in Fig. 1. The absorption of the test pulse is plotted as a function of the delay $\tau$ from the first IB pulse. The curves in the left panel are calculated as before with $T_{IB} = 1$ ps while for the right panel a value of $T_{IB} = 0.5$ ps has been used. In the latter case the absorption of the circularly polarized pulses clearly reflects the switching dynamics of the respective spin densities and the absorption of the linearly polarized test pulse essentially follows the evolution of the total subband occupation with a time resolution set mainly by the duration of the test pulse. The longer IB decoherence time in the left panel, however, results in coherent signal components that are superimposed on the signals. Even though the main features of the occupation dynamics are still visible, now additional oscillations appear which make such signals harder to interpret.

### 3. Conclusions

We have shown that it is possible to optically prepare CSBs with equal densities of opposite spin orientations. It is demonstrated that after this preparation the spins in a given subband can be switched by ISB pulses on a picosecond time scale. The spin switching can be realized keeping the total subband occupation almost constant when sufficiently short ISB pulses are used. For longer ISB pulses spins and charges in a given subband exhibit a periodic modulation. The oscillation of the total subband density is not expected in a model without Coulomb interaction and strongly depends on the CSB mass ratio when the Coulomb interaction is accounted for. Pump-probe type signals are suitable to monitor the predicted spin-sensitive dynamics, but may exhibit coherent features superimposed on the occupation dynamics.

### References

[1] Khurgin J B 2006 Appl. Phys. Lett. 88 123511
[2] Kaindl R A et al. 1998 Phys. Rev. Lett. 80 3575–8
[3] Murdin B N et al. 1997 Phys. Rev. B 55 5171–6
[4] Ohno Y, Terauchi R, Adachi T, Matsukura F and Ohno H 1999 Phys. Rev. Lett. 83 4196
[5] Vogel M, Vagov A, Axte V M, Seilmeier A and Kuhn T Phys. Rev. B accepted
[6] Bartel T, Gaal P, Reimann K, Woerner M and Elsaesser T 2005 Opt. Lett. 30 2805–7
[7] Sell A, Leitenstorfer A and Huber R 2008 Opt. Lett. 33 2767–9
[8] Ekenberg U 1989 Phys. Rev. B 40 7714–26
[9] Rossi F and Kuhn T 2002 Rev. Mod. Phys. 74 895–950