Spin Control in Semiconductors: Variations on a Theme

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***Abstract*— The manipulation of electron spins in semiconductors is a core concept in semiconductor spintronics. We review recent experiments that show how optical, electrical and exchange fields allow the control of spin-dependent phenomena in semiconductor devices. The first example addresses the all-electrical generation of electron spin polarization in conventional semiconductors via the spin-orbit interaction. Our experiments show that current-induced spin polarization and the spin Hall effect can be observed even in wide band gap semiconductors such as ZnSe, despite a relatively weak spin-orbit coupling parameter. The next example shows how circularly polarized photons allow us to both pump and probe spin polarized states in semiconductor microcavity lasers, resulting in the surprising finding that the spin dephasing time is correlated with the Q-factor of the cavity and the onset of stimulated emission. Finally, we discuss how we exploit the exchange interaction between local moments and band electrons to manipulate electronic and local moment spin dynamics in magnetic semiconductor quantum structures.**

***Index Terms*— semiconductor spintronics, spin Hall effect, magnetic semiconductor.**

I. Introduction

THE manipulation of spin polarized electronic states in semiconductor devices is of central interest to the development of "semiconductor spintronics," a research field aimed at utilizing electron spin in devices such as spin-based field effect transistors, spin-polarized light emitters and all-semiconductor magnetic tunnel junctions and spin valves [1-4]. Recently, discussions have begun to examine the potential advantages of such devices over existing semiconductor-based logic and metal-based spintronics technologies [5,6]. The basic exploration of semiconductor spintronic devices has led to a range of surprising fundamental discoveries in the past decade. Experiments in this context have revealed some important facts: spin polarized electrons can propagate across macroscopic distances (~100 μm) through homogeneous and inhomogeneous semiconductors [7,8], electron spin polarization can be generated in conventional semiconductor devices by simply flowing an unpolarized current [9,10,11,12], and spin polarized currents can be injected and detected in semiconductors using all-electrical techniques [13]. In addition, the use of optical pulses has enabled experimentalists to probe and manipulate the coherent dynamics of electronic, ionic and nuclear spin states in semiconductors [1]. Finally, the past decade has witnessed the emergence of new classes of ferromagnetic semiconductors wherein enhanced Zeeman splitting and ferromagnetism arises from the exchange interaction between band electrons and local moments (e.g. the 3d electrons in Mn) introduced within a semiconductor host lattice [4].

Here, we provide an overview of recent developments in the field, focusing on experiments that manipulate spins in semiconductors using a variety of methods, including spin-orbit coupling, photons, electric fields and the exchange interaction.

II. Spin Control in Semiconductors

A. Electrical generation of spin polarization in semiconductors.

The ability to manipulate carrier spins in semiconductors through the spin-orbit (SO) interaction provides a key means of all-electrical spin control in semiconductor spintronics, obviating the need for applied magnetic fields in potential spintronic devices. Spatio-temporally resolved Kerr rotation measurements allow the detection of electrically-induced spin polarization in semiconductors, and have been exploited for elucidating spin generation modes based upon SO coupling, most prominently current induced spin polarization [9] and the (extrinsic) spin Hall effect [10].

The first of these mechanisms -- current induced spin polarization (CISP) – results in a spatially uniform spin polarization when a conventional (spin unpolarized) current flows through a semiconductor crystal. This spin polarization can be detected by using Kerr rotation measurements that reveal the orientation of spin polarization in directions that depend on detailed device and crystal geometry [12]. CISP was first observed at cryogenic temperatures in GaAs [9] using the geometry shown in Fig. 1: a current flows along the x direction

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through a bar fashioned from a GaAs epilayer. We then use the Kerr effect to monitor the spin polarization along the z-direction (out of the plane of the sample). By applying a magnetic field in the plane of the sample (along x), any spin polarization oriented along y is forced to precess about the magnetic field. The resulting magnetic field dependence yields an odd Lorentzian shape, characterized by the spin lifetime and spin precession frequency (Fig. 1 (a)). The microscopic origins of the phenomenon are still not well understood, although it is believed that the SO coupling must play an important role. In an attempt to understand the role of SO coupling, we recently explored CISP in the wide bandgap semiconductor ZnSe, where the SO effects are expected to be significantly weaker than in GaAs. For instance, in ZnSe, the extrinsic SO parameter, as calculated from an extended Kane model, is 5 times weaker than that in GaAs. We expected CISP to be weak in the wide bandgap semiconductor ZnSe due to the weaker SO coupling parameter. However, we were surprised to find that the phenomenon is quite robust and that – unlike the case of GaAs -- it persists to room temperature [11] (as seen in Fig. 1(a)).

The second electrical spin generation mechanism -- the extrinsic spin Hall effect -- creates spin accumulation at the *edges* of a semiconductor transport channel by skew-scattering of an electric current. The phenomenon is again detected by measuring the spin polarization along z using the Kerr effect. A scanning optical Kerr microscope allows the spatial mapping of the spin Hall effect. The spin Hall effect was first demonstrated at cryogenic temperatures in GaAs and the observations are fully consistent with an extrinsic origin [10]. Despite the weaker SO coupling, we surprisingly discovered that – contrary to naïve expectations -- the optically measured spin Hall effect in ZnSe epilayers is readily observable and persists to room temperature (see Fig. 1 (b)).

The spin Hall effect is characterized by a spin Hall conductivity (defined in a manner analogous to conventional conductivity). The extrinsic spin Hall effect in semiconductors such as GaAs and ZnSe may be understood using a spin-dependent Boltzmann theory for skew scattering [14]. Such a calculation suggests that the comparable values of the spin Hall conductivity in GaAs and ZnSe may arise from a circumstantial combination of physical parameters such that the effect of reducing SO coupling is offset by accompanying changes in other parameters such as the effective mass of band electrons and screening. However, as far as we know, there is no current theory that explains the temperature dependence of the spin Hall effect and – in particular – the persistence of the spin Hall effect in a system such as ZnSe up to room temperature. Finally, it is relevant to note that the polarization produced by the spin Hall effect is still a few orders of magnitude too small for practical applications. Thus, it is paramount to gain a complete physical understanding of the phenomenon if we are to develop ways to enhance its magnitude for real devices.

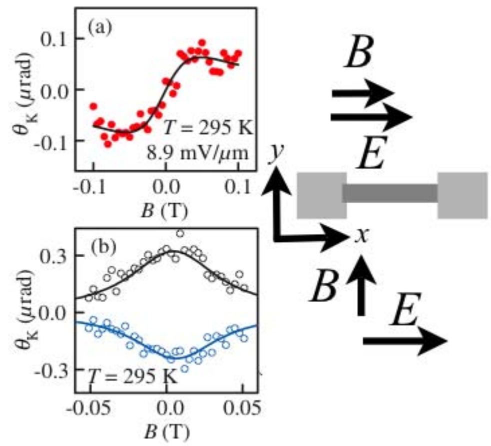

Fig. 1. Observation of (a) CISP and (b) the spin Hall effect in an n-ZnSe device. The device is a bar of length 0.235 mm and width 0.1 mm fabricated from a 1.5 µm thick n-doped ZnSe epilayer grown on a (001) GaAs substrate. In (b), the upper and lower curves are data taken from opposite edges of the sample. The adjacent cartoon illustrates the directions of the applied electric and magnetic fields in the two measurements. (Adapted from [11].)

B. Photonic control of spins in semiconductor microcavities

Semiconductor microcavities offer a unique means of controlling light-matter interactions, and have led to the development of a wide range of applications in optical communications and inspired proposals for quantum

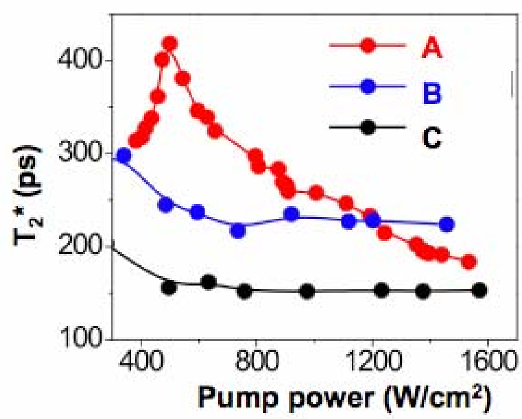

Fig. 2. Pump intensity-dependence of the spin coherence time T_2* measured in a GaAs/(Ga,Al)As microdisk containing IFQDs (A), a GaAs/(Ga,Al)As microdisk containing only QWs (B) and an unprocessed wafer (C) that contains the same heterostructure as in microdisk A. (Adapted from [15].)

information processing and computational schemes. Studies of spin dynamics in microcavities are relatively few, but have already revealed important new phenomena such as such as polarization beats and enhanced Faraday rotation. We have carried out a novel experiment [15] in this context by using the time-resolved Kerr effect to study the electron spin dynamics in optically-pumped GaAs microdisk lasers that contain quantum wells (QWs) and interface-fluctuation quantum dots (IFQDs) in the active region. We investigated how the electron spin dynamics are modified by the onset of stimulated emission in the disks, and observed an unexpected enhancement of the spin lifetime when the optical excitation is in resonance with a high quality (Q ~ 5000) lasing mode. Furthermore, the spin coherence time shows a maximum when the pump power coincides with the threshold for stimulated emission (Fig. 2). We found that the presence of IFQDs is a crucial aspect of these experiments, perhaps serving as a means to prevent carrier diffusion. This resonant enhancement, contrary to what is expected from the Purcell effect observed in the cavities, is then manipulated by altering the cavity design and dimensions.

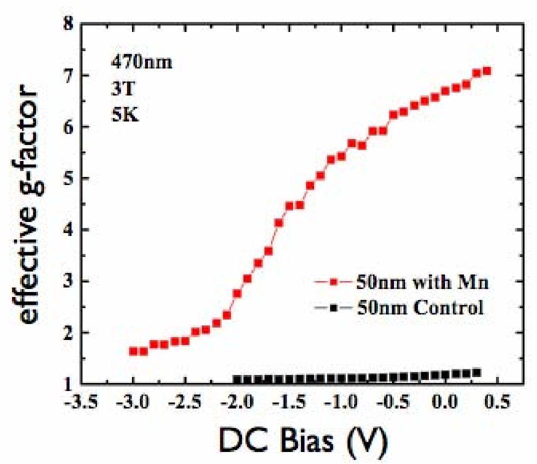

Fig. 3. All-electrical tuning of near-THz electronic spin dynamics in a magnetic parabolic quantum well. The central part of the quantum well contains a dilute distribution of Mn ions. Applying an electric field along the growth direction displaces the confined electron wave functions away from this central portion, reducing the carrier-ion exchange overlap and thus decreasing the effective electronic g-factor, as shown in panel (b). (Adapted from [16].)

C. Controlling spins in semiconductors via exchange interactions.

The introduction of magnetic ions into conventional semiconductor quantum structures such as QWs enhances the electronic g-factor because of exchange interactions between band electrons and the local moments [1]. This opens up opportunities for exploiting electric field tuning of the wave function overlap involved in the exchange interaction. We designed electrically gated parabolic quantum wells derived from Mn-doped II-VI semiconductors ZnSe and (Zn,Cd)Se and used time-resolved Kerr rotation to demonstrate the optical and electronic tuning of both the electronic and local moment (Mn^{2+}) spin dynamics in these structures [16]. By changing either the electrical bias or the laser energy, the electron spin precession frequency is varied from 0.1 - 0.8 THz at a magnetic field of 3 T and at a temperature of 5 K. An example of such data is shown in Fig. 3. Additionally, we demonstrated that such structures allow electrical modulation of local moment dynamics in the solid state, which is manifested as changes in the amplitude and lifetime of the Mn^{2+} spin precession signal under electrical bias. The large variation of electron and Mn-ion spin dynamics is explained by changes in magnitude of the *sp-d* exchange overlap.

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