Quantitative detection of electrically injected spin accumulation in GaAs using the magneto-optical Kerr effect

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Abstract

Using an ultra sensitive magneto-optical Kerr rotation setup we have observed electrical spin injection from (Zn,Mn)Se into bulk GaAs and quantified the spin injection efficiency. The current induced contribution was carefully separated from possible artifacts and studied as a function of voltage and external magnetic field. Our measurements allow us to estimate the concentration of the electrically injected spins into GaAs to be approximately $0.4 \times 10^{15}$ cm$^{-3}$ at a reverse bias of 0.7 V.

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The study of spin-dependent properties of semiconductors has become one of the hottest topics in physics due to their importance for the newly developing area of "semiconductor spintronics" [1, 2]. The main idea of "spintronics" is to use the fact that electrons have not only a charge but also a spin, yielding an additional degree of freedom for electronic devices. The realization of semiconductor spintronic devices, however, requires efficient electrical spin injection into a semiconductor, a task which is far from trivial and subject to intense research activity [3, 4, 5, 6, 7, 8, 9, 10]. Besides, to control and switch the magnetization using spin-polarized currents [11, 12], the spin accumulation at electrode/magnetic-layer interfaces is a crucial parameter [13], that however is hard to access experimentally.

Most optical studies of electrical spin injection into semiconductors so far were based on photoluminescence measurements. However, this method has considerable limitations regarding sample structure, quality, and spectral range [3, 4, 5, 6, 7, 8, 9, 10]. Moreover, the study of electrically injected spins based on photoluminescence can only be used to determine the presence or absence of spin-polarization of the injected current, while the spin accumulation or the number of injected spins is not accessible. The magneto-optical Kerr effect (MOKE), however, can be used to overcome all these limitations. Using MOKE spin injection and accumulation can be studied with no limitation with respect to sample and in a broad spectral and thermal range, including wavelengths were no luminescence can be measured [14, 15]. In this letter, we use a (Zn,Mn)Se/GaAs heterostructure to demonstrate that the magneto-optical Kerr effect is a powerful tool for the quantitative study of electrical spin injection. At a reverse bias of -0.7 V we observed a maximum spin-injection from a (Zn,Mn)Se electrode into GaAs of about $0.4 \times 10^{15}\text{cm}^{-3}$.

The magneto-optical Kerr effect is rotation of the polarization of light upon reflection from a magnetized sample. In terms of dielectric permittivity tensor $\epsilon$ the Kerr rotation $\theta_k$ can be presented as

\[ i\theta_k = \frac{2\epsilon_{xy}}{(n+1)^2n} , \]

where $n$ is the refractive index of the sample. It can be shown from the Onsager’s principles that only off-diagonal components of $\epsilon$ can be odd functions with respect to the magnetization of a medium. Neglecting terms of the higher order one can assume $\epsilon_{ij}^{(a)} \approx \alpha \cdot M$, and re-write equation (1) in the following form:

\[ i\theta_k = \frac{2\alpha M}{(n+1)^2n} \]
Normally for dia- and paramagnetic materials the magnetization of the medium is created by an external magnetic field. However, in the presence of spin injection, magnetization can be created by a nonequilibrium spin polarization as well. Thus, the magneto-optical Kerr effect can be a sensitive probe of the artificially introduced spin polarization in solids in general, and in semiconductors in particular.

The structure under investigation consisted of a paramagnetic (Zn,Mn)Se spin aligner on a conducting GaAs layer in an applied magnetic field. This field will Zeeman-split the conduction band levels in (Zn,Mn)Se leading to a, in principle 100%, spin polarized injection current from the (Zn,Mn)Se electrode into GaAs. The structure was based on a highly n-doped GaAs substrate onto which a n-type GaAs layer with a doping of $n=4\times10^{16}\text{cm}^{-3}$ and a thickness of 400 nm was deposited by molecular beam epitaxy. After deposition, the sample was transferred into a second growth chamber without breaking the UHV conditions. In this chamber a 100 nm (Zn$_{0.89}$Be$_{0.06}$Mn$_{0.05}$)Se layer was deposited which was also n-doped (approximately $n = 4 \times 10^{18}\text{cm}^{-3}$). In order to achieve a good ohmic top contact another 30 nm thick ZnSe layer with a n-type doping of $n = 2 \times 10^{19}\text{cm}^{-3}$ was deposited as a top layer. Again without breaking the UHV, the sample was transferred to a metallization chamber in which a metallization of Al, Ti, and Au was deposited by e-beam evaporation with layer thicknesses of 10 nm, 10 nm, and 30 nm, respectively. On top of this metallization a rectangular frame-like contact of 10 nm Ti and 250 nm Au was fabricated by optical lithography and lift off. Subsequently, Au and Ti inside the frame were removed by dry etching, leaving a transparent, but conducting window for the MOKE measurement. The layer sequence in the structure is virtually the same which was used for spin injection into a light emitting diode in [5]. It was used again in the present experiment because it typically yields a spin polarization of the injected current of up to 90 %.

For the MOKE measurement we used an ultrasensitive laser polarimeter. The light was incident from the side of the (Zn,Mn)Se electrode. After transmission though this spin injector the light was reflected from the (Zn,Mn)Se/GaAs interface. For the excitation a wavelength of 810 nm was chosen, because (Zn,Mn)Se is transparent at this wavelength, whereas the absorption in GaAs is quite large, yielding a maximum reflection at the (Zn,Mn)Se/GaAs interface (see inset in Fig. 1). Moreover, the photon energy at this wavelength is close to the exciton resonance in GaAs and all magneto-optical effects in this semiconductor of interest are resonantly enhanced. The sample was placed in a static magnetic field directed along
the growth direction of the sample aligning the spins in the (Zn,Mn)Se in the direction of the magnetic field. Rectangular current pulses with a repetition frequency of 400 Hz were sent through the structure and the rotation of the polarization of the reflected light was detected at the same frequency.

It should be noted that electrical injection of spins assumes the application of a voltage that would create relatively high electric fields in the studied structure, which, in turn, can also modify the dielectric permittivity tensor. Thus if one uses the magneto-optical Kerr effect for the study of the electrically injected spin polarization, a careful analysis of the observed effects and separating them from artifacts is necessary. Regarding the possible artifacts, the off-diagonal component of the dielectric permittivity tensor can be written in the following form, neglecting the higher-order terms:

\[ \epsilon_{ij}^{(a)} = \alpha M + \beta EH + \gamma I + \ldots, \quad (3) \]

where \( H \) is the external magnetic field, \( E \) is the electric field and \( I \) is the current. The off-diagonal component of the dielectric permittivity tensor can not be proportional to \( IH \)-component since it violates the Onsager’s principle. One can see that in case of spin injection into GaAs, the induced magnetization should be a linear function of the electrical current through the structure, as well as of the external magnetic field, since the latter affects the alignment of the spins in ZnMnSe, and thus determines spin polarization of the current. In principle, the term \( EH \) in Eq. (3) can manifest itself in the magneto-optical Kerr effect in a way similar to the electrically injected spin polarization. However, these two contributions into the Kerr effect can be clearly separated in the structures with a nonlinear \( I/V \)-characteristics.

Fig. 1 shows that the MOKE signal, induced by a spin polarized current in the (Zn,Mn)Se/GaAs heterostructure, depends linearly on the external magnetic field. This linearity originates from the fact that the spin injector (Zn,Mn)Se is paramagnetic. For magnetic fields used in our experiment, the paramagnetic susceptibility is far from saturation and the magnetization as well as the spin-injection efficiency are approximately proportional to the external magnetic field.

Fig. 2 shows the MOKE signal as a function of the current applied to the structure. One can see that for positive bias, i.e. current direction from the GaAs into (Zn,Mn)Se, no MOKE signal is detected. However, if the bias is negative and current flows from (Zn,Mn)Se
FIG. 1: MOKE signal at an applied voltage of 1.2 eV and a photon energy of 1.52 eV as a function of the external magnetic field. The inset shows the geometry of the experiment.

FIG. 2: MOKE signal as a function of the amplitude of the current pulses at a photon energy of 1.52 eV with an external magnetic field equal to 0.3 T. The inset shows the $I/V$-characteristics of the structure.

into GaAs, a pronounced MOKE signal is observed with a well distinguished maximum at 0.7 V.

The observed current dependence of the MOKE signal is in excellent agreement with the theoretical dependence of spin accumulation on injection current [17]. Only a minor spin accumulation is expected when the carriers flow from the GaAs into the (Zn,Mn)Se. In contrast, when the electrons flow from (Zn,Mn)Se into GaAs, spin polarized carriers of (Zn,Mn)Se are injected into the GaAs, causing a non-equilibrium spin accumulation in the
latter. The current dependence of this spin accumulation can be readily explained by taking into account several effects. At low bias transport occurs in the regime of linear response and consequently the spin accumulation is approximately proportional to the current. In this regime the spin accumulation can be described simply by the diffusion equation as in [18]. With increasing current the spin accumulation leads to a band bending at the \((\text{Zn,Mn})\text{Se}/\text{GaAs}\) interface which reduces the spin polarization because of a redistribution of spins between the two spin bands in the \((\text{Zn,Mn})\text{Se}\) [19]. At the current level where band bending starts to occur (at 0.7 \(V\)), a maximum of the induced spin accumulation is reached and thus a maximum in the MOKE signal is observed. For still higher bias, one is in the drift regime [20] where spin transport is characterized by an extension of the effective spin diffusion length due to the unscreened electric fields in the device. This leads to an increased penetration depth of the spin accumulation in the GaAs. However, once this non-linear regime is reached, the magnitude of the spin accumulation remains constant and hence the MOKE signal also does not increase further. These observations clearly demonstrate that the detected MOKE signal is indeed induced by the spin polarized current injected from \((\text{Zn,Mn})\text{Se}\) into GaAs, and not by the term proportional to \(EH\). Thus the magneto-optical Kerr effect is a measure of the efficiency of spin injection into semiconductors.

In order to estimate the efficiency of the electrical spin injection we used the optical orientation of the electron spins in GaAs as a reference. It is well known that under influence of circularly polarized light, a non-equilibrium spin polarization can be created in a semiconductor. For semiconductors with zinc-blend structure, such as GaAs, this phenomenon is well studied [21]. Therefore knowing the intensity and wavelength of the photoexcitation, one can estimate the number of photoinjected spin polarized carriers. Note that such an estimate also requires a detailed knowledge of the probabilities of the photoexcited transitions and the absorption coefficient of GaAs, but these are textbook values [22].

For our calibration experiment we have created spin polarized carriers by pumping with circularly polarized light and probed the resulting spin polarization with the magneto-optical Kerr effect in a pump and probe configuration. Details of the experiment were described elsewhere [14]. In brief, for the measurements a pulsed Ti:sapphire laser was used, with a pulse duration of approximately 100 fs and a repetition rate of 82 MHz, with a photon energy of 1.52 eV. Coherent pump and probe pulses with an intensity ratio of 10:1 were focused on the sample. The pump fluence on the sample was of the order of 10 \(\mu J/cm^2\) and
produced a spatially averaged nonequilibrium spin concentration of about \(0.7 \times 10^{17}\text{cm}^{-3}\). The Kerr rotation experienced by the reflected delayed probe pulse is measured as a function of the time delay between pump and probe pulses.

Fig. 3 shows the temporal behavior of the magneto-optical Kerr effect as a function of time delay between pump and probe pulses. It is well known that the photo-induced magneto-optical Kerr effect is sensitive not only to spin but also to carrier dynamics. Nevertheless, at a time delay of 15 ps one may expect that processes related to carrier dynamics are completed, while the spin relaxation of the photoexcited electrons is expected to be much longer. Thus the value of the Kerr rotation at a time delay of 15 ps can be taken as the one that corresponds to a spin concentration \(n_s = 0.7 \times 10^{17}\text{cm}^{-3}\). One can see from Fig. 3 that in GaAs at a photon energy of 1.52 eV and at a temperature of 10 K the spin concentration of \(n_s = 0.7 \times 10^{17}\text{cm}^{-3}\) results in a Kerr rotation of about \(10^{-4}\) rad. This ratio can be used for the calibration of the MOKE detection of electrically injected spins into bulk GaAs. Using this ratio between the Kerr rotation and spin concentration one can estimate that at conditions that corresponds to the maximum efficiency of the spin injection in our experiment \((U = -0.7\text{ V and } H = 0.3\text{ T})\) the concentration of the electrically injected spins is about \(0.4 \times 10^{15}\text{cm}^{-3}\).

In summary, using the example of the heterostructure (Zn,Mn)Se/GaAs we have demonstrated that the magneto-optical Kerr effect is a powerful tool for the study of electrical spin...
injection. We have shown a current induced contribution to the magneto-optical Kerr effect that arises from spin polarized carriers electrically injected from (Zn,Mn)Se into GaAs. This current induced contribution was carefully separated from possible artifacts and allowed us to estimate that the concentration of the electrically injected spins into GaAs is about $0.4 \times 10^{15} \text{cm}^{-3}$ for a voltage of 0.7 V and a magnetic field of 0.3 T.

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