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Electric-field induced modulation of the magneto-optical Kerr effect in a (Zn,Be,Mn)Se/GaAs spintronic device

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It is shown that when spin-polarized electrons are injected from a (Zn,Be,Mn)Se spin-aligner into GaAs, the magneto-optical Kerr effect from (Zn,Be,Mn)Se/GaAs spintronic device is strongly affected by a large electric-field at the (Zn,Be,Mn)Se/GaAs interface. This field causes the magneto-optical signal to be extremely sensitive to the sample temperature and the wavelength of the probing light. The observed temperature dependencies are explained in terms of the Franz-Keldysh effect at (Zn,Be,Mn)Se/GaAs interface. The findings demonstrate that the results of magneto-optical detection of electrically injected spins in spintronic devices can be easily misinterpreted if electric-field induced effects are not taken into account.

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The main idea of developing area 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.[1,2] 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.[3–10] 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.

Recently it has been shown that magneto-optical detection can be used to measure the spin accumulation and spin transport in lateral structures. These results are consistent with electrical measurements on the same samples and provide important insights in the spatial distribution of spin accumulation.[14–16] The magneto-optical detection may also allow one to estimate the concentration of electrically injected spins. All these studies on lateral structures clearly demonstrate that the magneto-optical Kerr effect (MOKE) is an efficient tool to investigate spin transport phenomena. However, real spintronic devices are mostly built in a planar geometry and the question is: can we use MOKE to study spin injection in such planar heterostructures?

Here we show that the MOKE signal from a (Zn,Be,Mn)Se/GaAs heterostructure under the condition of spin injection from (Zn,Be,Mn)Se into GaAs is indeed sensitive to the electrically injected spin polarization. However, the signal strongly oscillates as a function of temperature. Moreover, changing the voltage applied to the heterostructure changes this temperature dependence. A systematic study of both magneto-optical Kerr effect and reflectance shows that such a temperature and voltage behavior can be explained in terms of the Franz-Keldysh effect at the (Zn,Be,Mn)Se/GaAs interface. The application of a voltage to the structure results in both spin injection and a strong electric-field at the interface. This electric-field modifies both the optical properties and the magneto-optical response of the medium, while these changes in the optical and magneto-optical properties are a function of detuning between the photon energy of the probing light and the band gap of GaAs. Taking such a electric-field induced Kerr effect into account is crucial for a proper interpretation of the results of magneto-optical detection of spin injection. In particular, it is shown that changing the temperature one may reverse the sign of the Kerr effect, while the sign of the spin injection is not changed.

The structure under investigation consisted of a paramagnetic (Zn,Be,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,Be,Mn)Se leading to *a*, in principle 100%, spin-polarized injection current from (Zn-,Be,Mn)Se into GaAs. The structure was based on a highly *n*-doped GaAs substrate onto which an *n*-type GaAs layer with a doping of $n=4\times10^{16}$ 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 $n=4\times10^{18}$ cm^{-3}). In order to achieve a good ohmic top contact another 30–nm-thick ZnSe layer with an *n*-type doping of $n=2\times10^{19}$ cm^{-3} was deposited as a top layer. Both the (Zn,Be,Mn)Se and the ZnSe layer were *n*-doped with iodine using a Knudsen cell filled with ZnI_2. 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, 10, and 30 nm, respectively. On top of this metallization a rectangular framelike contact of 10 nm Ti and 250 nm Au was fabricated by optical lithography and lift off. Subsequently, the Au and Ti inside the frame were removed by dry etching, leaving a transparent, but conducting window for the MOKE measurements. The layer sequence in this structure is virtually the same as was used for spin injection into a light emitting diode in Ref. 5. Such a spin-LED typically shows a spin polarization of the injected current of up to 90%. The I/V-curve of the heterostructure [see inset in Fig. 1(b)] shows a diodelike characteristic. This diodelike behavior is due to band bending at the (Zn,Be,Mn)Se/GaAs interface, where electrons are depleted from the GaAs. This depletion layer is the origin of the built-in electric-field present in the 400-nm-thick GaAs layer.

For the measurements we used an ultrasensitive laser po-

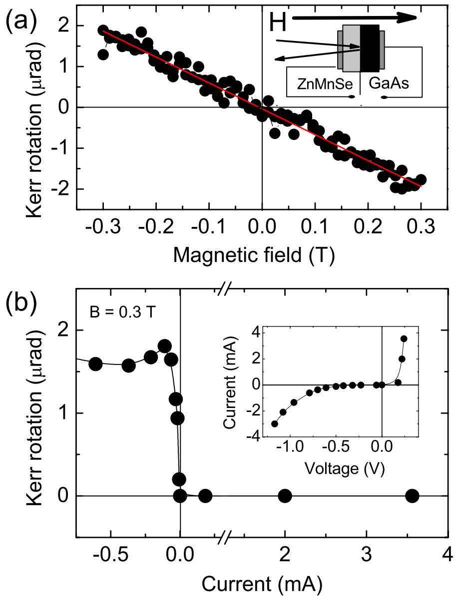

FIG. 1. (Color online) (a) Kerr rotation as a function of applied magnetic fields (inset shows a schematic picture of experimental configuration); (b) Kerr rotation as a function of current (magnetic field 0.3 T) [inset shows the I/V curve of the (Zn,Be,Mn)Se/GaAs heterostructure].

larimeter similar to the one described in Ref. 22. The light was incident from the side of the (Zn,Be,Mn)Se electrode. After transmission though this spin injector the light was reflected from the (Zn,Be,Mn)Se/GaAs interface. For the excitation a wavelength of 810 nm was chosen, because (Zn-,Mn)Se is transparent at this wavelength, while the absorption in GaAs is quite large, yielding a maximum reflection at the (Zn,Be,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 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,Be-,Mn)Se in the direction of the magnetic field. Rectangular current pulses with a repetition frequency f were sent through the structure and the rotations of the polarization of the reflected light as well as intensity of the reflected light were detected at the same frequency.

Figure 1(a) shows the Kerr rotation as a function of applied magnetic field for reverse bias at a current of about 3 mA. The observed linear dependence of the signal originates from the paramagnetic property of the (Zn,Be,Mn)Se spin injector, which is far from its saturation magnetization at these magnetic field strengths. Figure 1(b) shows the Kerr rotation as a function of current with a 0.3 T magnetic field applied. For reverse bias, spin-polarized electrons are injected from the (Zn,Be,Mn)Se layer into the GaAs layer resulting in a spin accumulation in the GaAs layer, as evidenced by the rapid increase in the Kerr signal. In the positive bias region no Kerr rotation is measured as electrons are injected from the GaAs into the (Zn,Be,Mn)Se layer, with no significant change in net spin polarization. In the range up to 0.1 mA the measurements of the Kerr effect as a function of electric current are consistent with the expectations that this magneto-optical effect is a probe of electrically injected spins. However, above 0.1 mA the dependence of the MOKE signal on current through the heterostructure becomes nonlinear and appears to saturate.

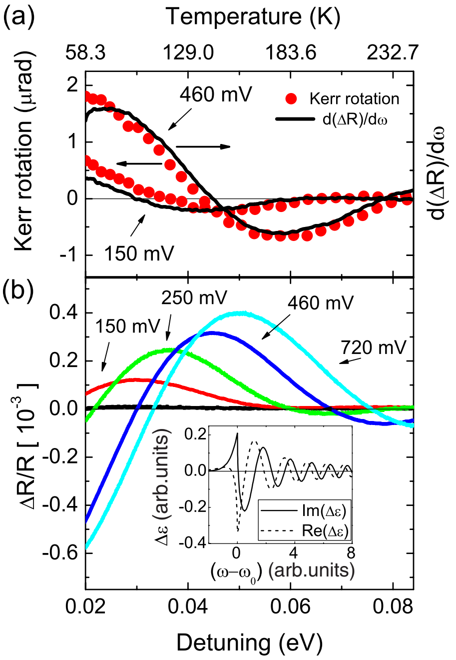

FIG. 2. (Color online) (a) Kerr rotation (dots) and derivative of the electroreflectance signal (line), and (b) the electroreflectance signal observed in GaAs for different applied voltages as a function of energy detuning. The inset shows the electric-field induced changes in the complex dielectric function as a function of band-gap edge detuning.

In order to understand the origin of such a nonlinearity we have studied the temperature dependence of the MOKE signal for different voltages applied to the structure. Note that the band gap of GaAs is temperature dependent and the sensitivity of MOKE to electrically injected spins is a function of the detuning between the photon energy of the probing light $\hbar\omega$ and the band gap $\hbar\omega_0$.[15] Therefore, in Fig. 2(a) instead of the Kerr rotation as a function of temperature we plot it as a function of detuning $\omega-\omega_0$. It is seen that the Kerr rotation changes periodically with increasing detuning. Moreover, if the voltage applied to the heterostructure is changed, this dependence changes.

It is important to note that application of a relatively low voltage to the heterostructure may result in strong electric-fields within the structure. For instance, assuming that the voltage drops over the least doped 400 nm GaAs layer, one may find that a voltage of about 150 mV results in an electric-field of about 1.25×10^5 V/m in this layer. Such a huge electric-field may easily modify the optical properties of a semiconductor in the vicinity of the band-gap energy due to the Franz-Keldysh effect. The latter results in a periodic modulation of the real and imaginary components of the dielectric permittivity as a function of the wavelength of light (see inset in Fig. 2). In order to reveal these electric-field induced changes we have measured the electric-field induced reflection ΔR from the structure as a function of temperature [see Fig. 2(b)]. Similarly to Fig. 2(a) the data are plotted as a function of detuning $\omega-\omega_0$. It is seen that the reflection $\Delta R/R$ also shows periodic behavior as a function of the detuning. This period is voltage dependent and the amplitude increases with increasing voltage.

Interestingly, the derivative of the reflection change with respect to the detuning $\omega-\omega_0$ appears to give a nearly perfect function to fit the dependence of the Kerr rotation on the detuning [Fig. 2(a)]. For diamagnetic materials it is well known that linear magneto-optical effects are proportional to the derivative of the refractive index: $\theta_K \propto dn/d\omega$.[17] In case of GaAs the real part of the refractive index is substantially larger than the imaginary part and the differential reflection can be written in terms of the real refractive index:

$$\Delta R \approx \frac{2}{n_0+1}\Delta n_V \tag{1}$$

where n_0 is the refractive index of GaAs and Δn_V is the electric-field induced change in the refractive index. It is seen that the derivative of the differential reflection is proportional to the derivative of the refractive index:

$$\frac{\Delta R}{d\omega} \propto \frac{d\Delta n_V}{d\omega} \propto \frac{dn_V}{d\omega} \propto \theta_K. \tag{2}$$

This clearly shows that the behavior of the magneto-optical effect observed experimentally can be understood in terms of an electric-field induced modulation of the reflectivity of the GaAs layer in the heterostructure.[18–21] The modulation originates from the strong electric-field drop over the low conductivity GaAs layer and the Franz-Keldysh effect.

These observed electric-field induced changes in the MOKE signal have important implications for the magneto-optical detection of electrically injected spin-polarized carriers in planar spintronic heterostructures and devices. This is demonstrated in Fig. 3, where the MOKE signal for reverse bias is plotted for two different temperatures. Figure 3 clearly shows that due to the electrically induced changes of the magneto-optical Kerr effect, the sign of the signal can be easily changed while the sign of the spin polarization has not been altered. In order to retrieve correct information about the spin polarization from the measured magneto-optical signal, a full spectral analysis of the complex refractive index and the changes due to the Franz-Keldysh effect is required.

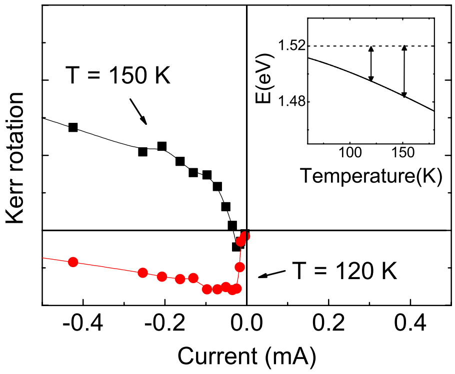

FIG. 3. (Color online) Kerr rotation as a function of applied voltage for 120 and 150 K. The inset shows the detuning (arrows) of the temperature-dependent band-gap edge (solid line) with respect to the laser wavelength (dotted line).

In conclusion, the magneto-optical Kerr effect from (Zn,Be,Mn)Se/GaAs heterostructure under the condition of spin injection from (Zn,Be,Mn)Se into GaAs has been investigated. The method appears to be very sensitive to electrically injected spin polarization. However, even a qualitative analysis of the magneto-optical measurements of the electrically injected spins in these structures is seriously hampered by electric-field induced changes of the optical and magneto-optical properties. Although voltages applied to the heterostructure are relatively small, most of the voltage drops over the 400 nm GaAs layer with the minimum conductivity. This result in an electric-field induced modulation of the optical properties of this layer due to Franz-Keldysh effect. Taking such an electric-field induced Kerr effect into account appears to be crucial for the interpretation of the results of magneto-optical detection of spin injection. In particular, it is shown that changing the temperature one may reverse the sign of the Kerr effect, while the sign of the spin injection is not changed.

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