Spin noise spectroscopy in GaAs

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We observe the noise spectrum of electron spins in bulk GaAs by Faraday rotation noise spectroscopy. The experimental technique enables the undisturbed measurement of the electron spin dynamics in semiconductors. We measure exemplarily the electron spin relaxation time and the electron Landé g-factor in n-doped GaAs at low temperatures and find good agreement of the measured noise spectrum with an unpretentious theory based on Poisson distribution probability.

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The inexorable decrease of structure size in semiconductor devices inevitably leads from today’s quasiclassical devices to quantum mechanical devices. These quantum mechanical devices might rely not only on the charge of electrons, i.e., on the spatial part of the electron wave function, but also on the much more robust spin part of the wave function. The robustness of the electron spin motivates the current extensive research on the spin dynamics in semiconductors and might lead to spintronic devices with superior functionality and to the enshining goal of spin quantum information processing [1, 2, 3].

One important signature of the spin dynamics in semiconductors results from the thermal fluctuations of electron spin occupation in the conduction band which fluctuates on the time scale of the spin lifetime and gives rise to spin noise. This kind of spin noise has been observed recently in rubidium gas atoms [4] and theoretically exploited for spin currents through single quantum dots [5]. The experimental observation of spin noise in semiconductors is however a major challenge since the photon shot noise in optical experiments and the Coulomb shot noise in electrical experiments is usually orders of magnitude larger than the spin noise. On the other hand, measurement of the spin noise in semiconductors has the power to become an important experimental tool since the spin noise spectrum yields not only information about the electron Landé g-factor but also promises to give insight into electron-electron spin correlations, spin phase transitions, and spin fluctuations in low-dimensional semiconductor structures. Additionally, spin noise spectroscopy has the advantage to detect optically the spin dynamics in semiconductors without optical excitation of electrons and holes.

This Letter presents an experimental and theoretical description of the spin noise in semiconductors. The experimental setup is schematically depicted in Fig. 1. The optical measurements are performed on a 370 µm thick GaAs wafer with a silicon n-doping of $1.8 \times 10^{16}$ cm$^{-3}$ by Faraday-rotation spectroscopy. The light of a cw laser diode is sent through a spatial filter, linearly polarized by a Glan Thompson polarizer, and focused on the GaAs sample which is mounted in Voigt geometry in a superconducting split-coil magnet with variable temperature insert. The laser wavelength is tuned 10 nm below the GaAs band-gap to minimize absorption and maximize the Faraday rotation signal. The focus diameter of the laser is about 65 µm. The linearly polarized light passing through the sample is split by a polarizing beam splitter into two components, linearly polarized $\pm 45^\circ$ with respect to the initial polarization. The two components are focused on a pair of photo diodes of a NewFocus 650 MHz balanced photo receiver and the time varying difference of the two equally strong if temporally averaged components is converted with a gain of 350 V/W into voltage and measured by an HP spectrum analyzer.

FIG. 1: (color online) Schematic of the experiment. Thermodynamic fluctuations of the electron spins in n-doped GaAs precess around an external magnetic field. The precessing spin fluctuations cause oscillations of the Faraday rotation signal $\Theta_F$ whose power spectrum is detected by a balanced receiver and a spectrum analyzer.
propagation. The spin noise strongly depends on the magnetic field since any statistical imbalance of the electron spin ensemble precesses around the magnetic field resulting in a spin noise peak at the precession frequency. The width of the spin noise peak is proportional to the spin relaxation rate, which includes diffusion of the thermal spin fluctuations out of the laser focus. The white photon and electron noise powers do not depend on the magnetic field and therefore can be easily subtracted.

Figure 2 depicts the measured spin noise spectra for three magnetic fields. The power spectrum at each magnetic field is averaged over 62 measurements ± 10 minutes and subtracted by interleaving 62 measurements ± 10 minutes at zero magnetic field to subtract the photon and electrical noise. We alternate between finite and zero magnetic field to eliminate any influence of thermal drift in the electronics. The spin noise maxima in Fig. 2 shift linearly with $B$ since the spin precession frequency and therefore the spin noise frequency is directly proportional to $B$. The width of the spin noise spectra is about 7 MHz yielding a spin relaxation time of about 45 ns. This spin relaxation time is consistent with earlier measurements by Dzhioev et al. who measure 50 ns for localized donor bound electrons in GaAs with an $n$–doping of $1.5 \times 10^{16}$ cm$^{-3}$.

Figure 3 depicts the maxima of the spin noise peaks versus $B$. The spin precession frequency is equal to $g_e\mu_B B/h$, where $g_e$ is the electron Landé $g$–factor, $\mu_B$ is Bohr’s magneton, and $h$ is Planck’s constant. The slope of the measured noise frequency $f$ versus $B$ yields $g_e = -0.41 \pm 0.01$ which is in excellent agreement with optically oriented and detected electron spin resonance in lightly doped $n$–GaAs confirming that the measured spin noise is in fact correlated with donor bound electrons. The width of the noise spectra is a measure of the spin relaxation time (right inset in Fig. 3), which is within the measurement error independent of $B$, i.e., the spin relaxation measurement is not obscured by inhomogeneous broadening of $g_e$.

In the following, we want to theoretically estimate the amplitude of the spin noise and compare the results with our measurements. We make the simplifying assumption that the statistical fluctuation of the electron spin polarization along the light propagation is proportional to $\sqrt{N}$, where $N$ is the number of donor bound electrons in the volume $V$ of the laser. In our experiment, this is a good approximation since the electrons are localized at the donors and the Poisson prerequisite of independent events is therefore fulfilled. The experiment fortifies the assumption since we do not observe a temperature dependence of the width and the height of the noise peak when we increase the temperature from 5 K to 10 K, i.e., the area under the noise peak stays constant. The localization of the electrons has additionally been verified by temperature dependent transport measurements. We calculate the change of the valence band to donor absorb-
where DOS is the density of states. For Fermi–Dirac element for transitions between Bloch states, $E_v = (\hbar^2 + E_D - E_g)$, $E_D = 0.06$ meV the donor binding energy, $E_g = 1.517$ eV the direct band gap energy, $m_{hh} = 0.45 m_0$ and $m_{lh} = 0.082 m_0$ the heavy and light hole masses, respectively, $n = 3.6$ the refractive index, $c$ the velocity of light, $\omega$ the light frequency, $m_0$ the free electron mass and $m_e = 0.067 m_0$ the effective electron mass in the conduction band. The minus sign results from the optical selection rules which couple for a given circular polarization heavy hole and light hole to opposite electron spin states. Applying Kramers–Kronig relation to $\Delta \alpha$ yields the average change in refractive index for right– ($\sigma^+$) and left–circularly ($\sigma^-$) polarized light and thereby the average Faraday rotation angle. The change of refractive index $\Delta n$ at 825 nm due to the thermal fluctuations becomes in our sample $\Delta n \approx 2.4 \times 10^{-8}$ and the resulting Faraday rotation angle $\Theta_F = \approx 7 \times 10^{-5}$ rad. The calculated maximum of the noise peak for a spin relaxation time of 45 ns is $9 \times 10^{-17}$ V$^2$/Hz. This calculated noise is for the simplicity of the calculation, which does not include trionic effects [10], and the uncertainties in the experimental parameters in good agreement with the measured $1.5 \times 10^{-17}$ V$^2$/Hz.

All measurements have been carried out at low temperatures where electrons are localized and the noise signal is temperature independent. At higher temperatures the donor bound electrons become delocalized and the distribution of the electrons in the conduction band follows a Maxwell–Boltzmann distribution. The average size of fluctuations $\sigma_{N^+ - N^-}$ of the absolute spin orientation is expected to be for the Maxwell–Boltzmann distribution - as in the localized case - temperature independent and equal to $N$. Nevertheless, the Faraday rotation signal should become temperature dependent since $\Delta \alpha$ broadens and moves in energy with increasing temperature. The independence of $\sigma^2$ on temperature will change to a strong temperature dependence in samples with higher electron densities where the electron distribution is a Fermi–Dirac distribution $f(E)$ with

$$\sigma_{N^+ - N^-}^2 = \frac{V}{\sum_{E_{\exp}}^{\infty}} \text{DOS}(E) f(E)(1 - f(E)) dE,$$  \hspace{1cm} (2)

where DOS is the density of states. For Fermi–Dirac distributions,

$$\lim_{T \to 0} \sigma_{N^+ - N^-} = 0 \quad \text{and} \quad \lim_{T \to \infty} \sigma_{N^+ - N^-} = \sqrt{N},$$

with a most pronounced temperature dependence between $T = 0$ and $k_B T \leq E_F$, where $k_B$ is Boltzmann’s constant and $E_F$ is the Fermi energy.

We expect spin noise spectroscopy to have a wide range of applications in semiconductors. As an example we show in the following that spin noise is in principle capable to measure intrinsic electron spin relaxation times at low temperature with less uncertainties than traditional Faraday rotation or Hanle measurements. The intrinsic electron spin relaxation time recently gained new interest, since experiments and calculations by Beck et al. at 4 K adumbrate that the electron spin relaxation times in GaAs with an $n$–doping in the range between $10^{15}$ cm$^{-3}$ and $10^{16}$ cm$^{-3}$ might not be limited by the anisotropic exchange interaction [11] but by the Dyakonov–Perel (DP) mechanism [12]. The DP mechanism vanishes for electrons with wave vectors $|\vec{k}| \to 0$. Therefore low electron temperatures and the absence of additional spin relaxation mechanism are required for long spin relaxation times. These requirements are extremely difficult to achieve in traditional Faraday rotation and Hanle measurements for two reasons. Firstly, the carrier temperatures are intrinsically higher than the sample temperature and secondly, the optically injected holes cause additional spin relaxation due to the well known Bir–Aronov–Pikus (BAP) mechanism [13]. The temperature of the optically injected carriers are at low sample temperatures intrinsically higher than the sample temperature since even resonant optical excitation (excitation of the $n$–doped semiconductor at the Fermi edge) yields hot holes with high $k$ values and carrier cooling at low temperatures is extremely inefficient due to the in-
To evidence that spin noise measurements are sufficiently sensitive even below the band tail absorption, we have calculated the Faraday rotation noise signal in dependence on wavelength (see Figure 4). The noise power decreases by two order of magnitude when we increase the excitation wavelength from 825 nm to 840 nm. At 825 nm about 90% of the light is absorbed in our 370 µm thick GaAs sample yielding an excitation density of $5 \times 10^{14}$ cm$^{-3}$ assuming a radiative carrier life time of 10 ns. At 840 nm the absorption is nearly negligible. We have also calculated the Faraday rotation signal for non-localized electrons, e.g. in modulation doped GaAs, and find at the same electron temperature a signal decrease of only one order of magnitude at 840 nm and two orders of magnitude at 900 nm. We have to compare these decreases in noise power signal with the signal–to–noise ratio in Fig. 2. Keeping in mind the deficiencies of our present experiment we are confident that even two orders of magnitude lower doping concentrations should be measurable since the noise signal decreases only with the square root of the doping concentration.

In conclusion, we have measured the spin dynamics in $n$–doped bulk GaAs by spin noise spectroscopy. The sensitive technique allows the disturbance free measurement of the spin dynamics in semiconductors with high accuracy. The measurements show in combination with calculations that spin noise spectroscopy in semiconductors is a powerful tool, circumvents common problems of carrier heating and injection of interfering holes, and promises new insight into spin relaxation, magnetization dynamics, and electron–spin correlations.

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