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# Spin Noise Spectroscopy in N-GaAs: Spin Relaxation of Localized Electrons *

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*Spin noise spectroscopy (SNS) of electrons in n-doped bulk GaAs is studied as functions of temperature and the probe-laser energy. Experimental results show that the SNS signal comes from localized electrons in the donor band. The spin relaxation time of electrons, which is retrieved from the SNS measurement, depends on the probe light energy and temperature, and it can be ascribed to the variation of electron localization degree.*

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Spintronics has attracted intense attention as a promising candidate for information storage, processing, and transmission.[1,2] A key factor to realize spin-based devices is to find proper semiconductor materials with long spin relaxation time (SRT), which thus has to be measured properly. The Hanle effect and the time-resolved Faraday/Kerr rotation (TRFR/TRKR) spectroscopy are powerful tools, which directly measure the SRT and spin precession frequency of the carriers with an external magnetic field.[3] However, both methods have to excite the sample to create a preferential spin orientation in it, thus demolishing the intrinsic spin dynamic.[4] Spin noise spectroscopy (SNS), a new kind of the Faraday rotation (FR) technique, has successfully circumvented the disadvantage. It uses a below-band-gap laser as the probe light to sense the stochastic spin noise of the carrier in thermal equilibrium.[5]

Although SNS was first carried out in atom optics,[6] the method is especially helpful to semiconductor physics since it allows one to study spin dynamics without extra spin injection. Since the first SNS measurement in semiconductors was demonstrated in n-type bulk GaAs by Oestreich *et al.*,[7] many works have been reported on the SNS of three-, two-, and zero-dimensional semiconductor systems, as a result of the remarkable progress in digital hardware of data acquisition.[5] Lucivero *et al.* further improved the signal-to-noise ratio (SNR) of SNS by using squeezed-light as the probe.[8] Two-color SNS, which uses two probe lasers, enables researchers to study the correlated spin fluctuations in spin ensembles.[9,10] Li *et al.* have used high order SNS to reveal essentially new information about correlated spin systems.[11–13] The SNS is now looking for its niche among other methods of magnetic resonance spectroscopy and turning into a standard experimental technique with a wide and unique range of applications with the ever improving SNR.[14–16]

Previous studies of SNS in n-GaAs have been focused on the spin relaxation of electrons in conduction bands.[4,17] In this Letter, we put emphasis on the spin relaxation of localized electrons in the donor band of n-GaAs. We measure the spin relaxation time (SRT) of electrons in n-doped bulk GaAs via a self-made SNS system based on the sub-band gap Faraday rotation effect. Frequency spectra of electron spin noise are measured and analyzed as functions of temperature and the probe-laser energy. Our experimental observations suggest that the SNS signal mainly comes from the localized electrons in the donor band. The dependence of electron SRT on the probe light energy and temperature comes from the variation of electron localization degree.

The basic idea of SNS in a weakly doped semiconductor can be understood as follows: the spin distribution of an ensemble of $N$ noninteracting electrons in thermal equilibrium follows the Poisson distribution. Statistical fluctuations of the $N$ spins should generate spin polarization with an average magnitude of $\sqrt{N}$. Such a spin polarization changes in magnitude and orientation on a time scale of the electron SRT. Its projection along the light propagation direction leads to unequal refractive indices for right ($\sigma-$) and left ($\sigma+$) circularly polarized lights and thus a rotation of linearly polarized light passing through the sample (Faraday rotation, FR). Such FR variations are converted to voltage signals via the combination of a Wollaston prism and a balanced photodiode bridge. The electrical signal is then collected, computed (Fast Fourier Transform, FFT) and accumulated in real time by a field programmable gate array (FPGA)-based data acquisition card (DAC) and finally sent to a computer. Figure 1(a) depicts schematically the experimental setup for SNS measurements in n-GaAs, similar to those used to detect spin noise spectra in rubidium atomic gases.[6,18,19]

The linearly polarized probe light comes from a

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Ti:sapphire cw tunable laser. The laser is tuned to the transparent region below the band gap of bulk GaAs ($E_{\rm gap} \sim 1.514$ eV or 819 nm at $T = 6$ K). It is focused with a 20-mm-focal-length lens through the n-GaAs wafer, which is mounted on the variable-temperature insert of an optical $^4$He cryostat. Two commercial, silicon doped n-GaAs wafers are used in this work: sample A has a doping concentration of $2.4 \times 10^{16}$ cm$^{-3}$ and a thickness of 260 μm, while sample B has a doping concentration of $6.2 \times 10^{16}$ cm$^{-3}$ and a thickness of 500 μm. The doping concentration of both samples is slightly larger than the critical concentration of metal-insulator transition in n-GaAs, where electron SRT is known to be rather long at low temperature.[20,21]

A magnetic field, transverse to the light propagation direction, shifts the peak of the spin noise from zero to the Larmor precession frequency $\omega_{\rm L} = g\mu_{\rm B}B/\hbar$, where $g$ is the Landé factor, $\mu_{\rm B}$ is the Bohr magneton, $B$ is the external magnetic field and $\hbar$ is the Planck constant. Each spin noise spectrum demands two spectra: one ($S_1$) is measured in the target transverse magnetic field, while the other ($S_2$) is measured in a background field $B \sim 1500$ G that shifts the spin noise out of the frequency range of interest. Each spectrum is typically averaged for 15 min. Here $S_2$ is subtracted from $S_1$ to remove the background. Figure 1(b) shows a typical spin noise spectrum from sample A. It can be well fitted by a single Lorentzian curve. The full width at half maximum (FWHM) $\omega_{\rm F}$ yields the transverse SRT $\tau_{\rm spin} = 1/(\pi\omega_{\rm F})$. The peak position $\omega_{\rm L}$ gives effective $g$-factor $g^* = \hbar\omega_{\rm L}/\mu_{\rm B}B$.

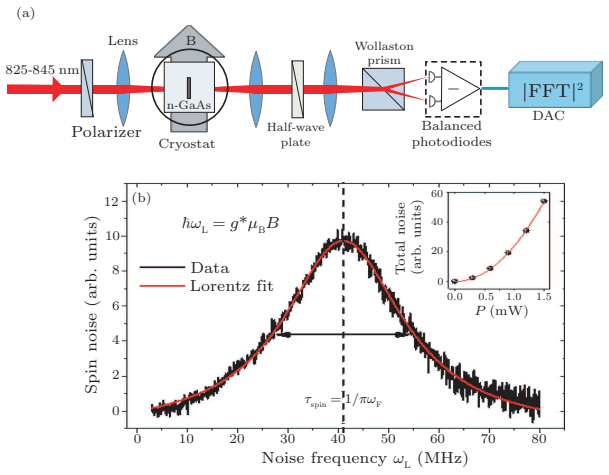


**Fig. 1.** (a) Experimental setup for spin noise spectroscopy in semiconductors. (b) Typical spin noise spectrum for sample A. The spectrum is taken at $B = 66$ G, $T = 6$ K using the FPGA-based DAC with laser wavelength $\lambda = 830$ nm (1.494 eV). Laser power $P = 1$ mW. The background has been eliminated by subtracting spin noise spectrum measured with $B \sim 1500$ G. Measurement is for 2×15 min. Inset: the integrated spin noise power versus the probe light intensity.

The inset in Fig. 1(b) shows the SNS signals of sample A measured with different probe light intensities from 0.3 to 1.5 mW. The integrated area under these spectral peaks as a function of the probe light intensity can be well fitted by a parabola, indicating that the relationship between SNS signal and FR signal is $S \propto F^2$ since the data from the FPGA-based DAC is Fourier spectra squared.[18,19] The total spin noise $S \propto I^2$, because the FR signals $F \propto (I \cdot \delta\theta_{\rm F})$, where $I$ is the probe light intensity and $\delta\theta_{\rm F}$ is the FR angle.

Figure 2 shows electron spin noise spectra from n-GaAs with different transverse magnetic fields $B$. The spin noise peak shifts to higher frequencies with increasing the magnetic field $B$, as shown in Fig. 2(a). The peak position moves linearly with the magnetic field $B$ as expected from $\omega_{\rm L} = g\mu_{\rm B}B/\hbar$. The half width $\omega_{\rm F}$ of the SNS with various magnetic fields in Fig. 2(a) is about 28.8 MHz, giving an SRT of about 11 ns for sample A at temperature $T = 6$ K and laser wavelength $\lambda = 830$ nm (1.494 eV). The SRT does not depend on altered $B$ because of the small variation range (0–110 G) of the magnetic field.[20]

The spin noise frequency versus the magnetic field $B$ is shown in Fig. 2(b) for the two samples. Their slopes yield $|g^*| = 0.443 \pm 0.02$ for sample A and $|g^*| = 0.405 \pm 0.02$ for sample B, respectively, in good agreement with the results measured by TRKR.[22] The difference of $g^*$ between the two samples results from the difference between their doping concentration and thus Fermi energy levels.[4]

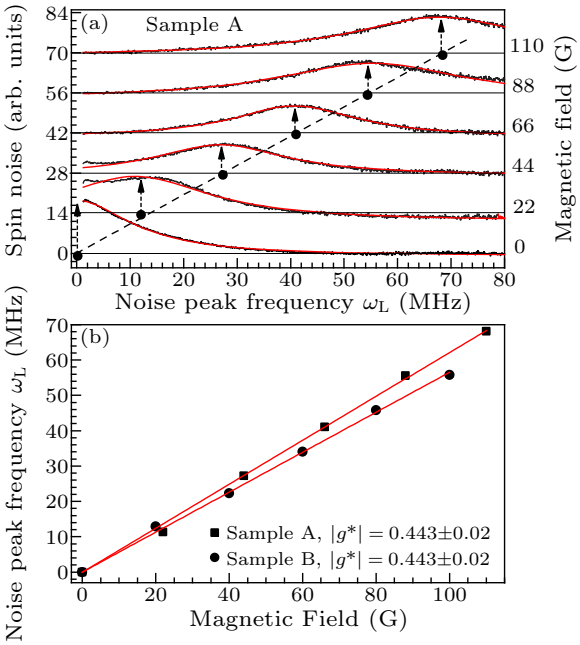


**Fig. 2.** Spin noise spectra in various magnetic fields. The sample temperature $T = 6$ K, laser power $P = 1$ mW and laser wavelength $\lambda = 830$ nm (1.494 eV) for sample A and $\lambda = 839$ nm (1.478 eV) for sample B. (a) Electron spin noise spectra from sample A in various magnetic fields. (b) The peak frequency of these spin noise spectra versus $B$ for samples A and B. Their slopes reveal the electron effective $g$-factor $|g^*|$.

Figure 3 shows the SNS signals and the absorption spectra measured with different energies of the probe light $E_{\rm p}$ for the two samples. Figures 3(a) and 3(c)

show the spin noise power versus $E_{\rm p}$. Figures 3(b) and 3(d) show the absorption spectra. The optical absorption cannot be neglected in the region of energy above 1.492 eV for sample A and 1.478 eV for sample B. The absorption below the band gap arises from tail states and it increases with $E_{\rm p}$, namely, the states density of electrons $\rho(E)$ increases. The concentration of electrons is given by $n(E,T) = \frac{\rho(E)}{e^{(E-E_{\rm F}/k_{\rm B}T)}+1}$, where $E$ is the electron energy, $E_{\rm F}$ is the Fermi energy, $k_{\rm B}$ is the Boltzmann constant, and $T$ is the temperature.[23] The SNS signal comes from the electrons whose energies are close to the probe light energy. The probed electron concentration increases as $E_{\rm p}$ moves closer to the conduction band since $\rho(E)$ increases. However, when the light absorption is not negligible, the noise power intensity becomes smaller since the optical absorption becomes larger as $E_{\rm p}$ increases.

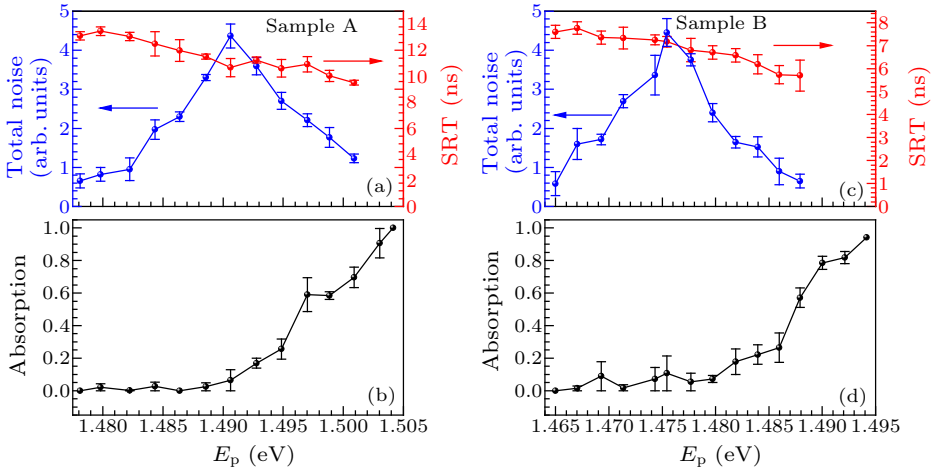


**Fig. 3.** SNS of n-GaAs with different energies of probe light. Here $T = 6$ K, $B = 66$ G, laser power $P = 1$ mW. Dependence of absorption, spin relaxation time and spin noise power on the energy of the probe light for sample A [(a), (b)] and sample B [(c), (d)].

Figures 3(a) and 3(c) also show the dependence of SRT on $E_{\rm p}$. As $E_{\rm p}$ moves closer to the GaAs band gap, the SRT of sample A decreases from 14 ns to 9.5 ns for sample A and from 8 ns to 5.8 ns for sample B. It can be ascribed to that the spin noise signal comes from different electrons with varying degrees of localization. We suggest that the spin noise signal mainly comes from the electrons in the donor band, which are localized by the impurity centers (electrons transition to the conduction band are inefficient at low temperatures). The basic mechanisms of electron spin relaxation in GaAs, D'yakonov–Perel' (DP) and Elliott–Yafet (EY) mechanisms are suppressed since the electron orbital motion in the donor reduces the scattering probability of electrons with other particles.[24] Furthermore, the Bir–Aronov–Pikus (BAP) mechanism is irrelevant as there are few holes in the n-type GaAs.[25] The circumstance mentioned above leads to long SRT of localized electrons. As $E_{\rm p}$ increases, the electron probed by the light is closer to the conduction band and its ionization energy decreases. In other words, the SNS signal comes from the electrons whose (localized) wave functions spread much further, and the scattering probability of electrons becomes larger, thus reducing the SRT. The SRT of sample A is longer than sample B, because of the same scattering mechanism since the doping concentration of sample A is smaller than that of sample B.

Figure 4 shows the temperature dependence of electron SRT measured by SNS. As temperature rises from 6 K to 30 K, the electron SRT decreases from 12.8 ns to 7.5 ns for sample A and from 8 ns to 6 ns for sample B. It can be interpreted by the linewidth broadening of the electron energy level. The electron kinetic energy increases with the rising temperature, namely, the thermal fluctuations become stronger. The state density of electrons with higher energy is larger than that with lower energy, thus contributing more to the SRT.

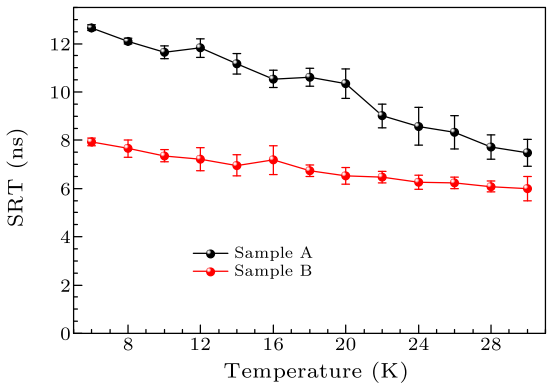


**Fig. 4.** Electron spin relaxation time of samples A and B as a function of temperature in n-GaAs. Here laser wavelengths are set to $\lambda = 830$ nm (1.494 eV) for sample A and $\lambda = 839$ nm (1.478 eV) for sample B, laser power $P = 1$ mW, and magnetic field $B = 66$ G

However, the spin relaxation of electrons due to

the increasing temperature is faster than that due to the increase of $E_{\rm p}$. Taking sample A, for example, the SRT changes about 4.5 ns (from 14 ns to 9.5 ns) with $E_{\rm p}$ increasing about 22 meV (Fig. 3(a)). As temperature rises from 6 to 30 K, the average kinetic energy of electrons increases about 8 meV ($4k_{\rm B}T$), but the SRT changes about 5.3 ns (from 12.8 ns to 7.5 ns). We ascribe this to more scattering of electrons in higher temperatures.

In conclusion, we have studied the spin noise spectroscopy of electrons as functions of temperature and probe-laser energy in n-doped bulk GaAs. The below-band-gap laser probed the SNS of the localized electrons in the donor band. The electron SRT dependence on the probe light energy and temperature comes from the variation of electron localization degree.

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