Measuring the Stochastic Spin Noise of Free Electrons in Semiconductors

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In magnetic systems, fundamental noise can exist in the form of random spin fluctuations. In his seminal 1946 paper on nuclear induction, Felix Bloch noted that random, statistical fluctuations of N paramagnetic spins should generate measurable noise of order $N^{1/2}$ spins, even in zero magnetic field. By the fluctuation-dissipation theorem, this "spin noise" alone contains detailed information about the spin system itself. (The fluctuation-dissipation theorem states that the response of a system to an external perturbation -- *i.e.*, the susceptibility -- can be described by its spectrum of fluctuations while in thermal equilibrium). We use magneto-optical techniques to passively and sensitively "listen" to the magnetization noise of free electrons in a solid-state system: n-type GaAs. Correlation spectra of the measured spin noise reveals important properties of electron spins (for example, g-factor and spin lifetime), without having to excite, pump, or otherwise drive the system away from thermal equilibrium.

Compared with the spin noise signals that have been measured in alkali vapors [1], the noise signals from spins in GaAs are extremely small. We have therefore developed a digital spectrum analyzer with real-time bandwidth approaching 100 MHz. Compared with commercial (sweeping) spectrum analyzers, this instrument realizes an increase in data throughput by a factor of at least 100 (and consequently, a reduction in averaging time by a factor of 100). This allows to reveal the tiny spin fluctuations from a very small number of fluctuating electrons in n-GaAs.

Conventional RF spectrum analyzers mix a reference oscillator with the incoming signal in order to measure signal power at a particular frequency. The reference oscillator is then swept over the frequency range of interest in order to generate a spectrum. In effect, this scheme ignores most of the data most of the time, because only one particular frequency is analyzed at any particular instant. E.g., using a 1 MHz resolution bandwidth to sweep from 0-200 MHz, ~99.5% of the data is effectively being ignored at any given time.

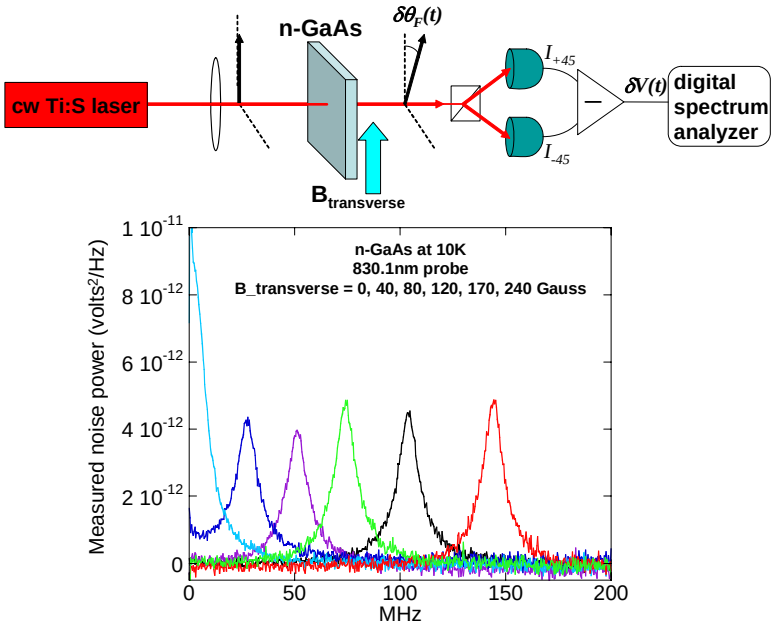

Figure 1:Experimental setup. Stochastic spin fluctuations of electrons in n-type GaAs precess about the applied transverse field, imparting Faraday rotation fluctuations on the transmitted probe laser, which are measured in a sensitive optical bridge. Below: measured spin noise from n-GaAs at 10K at various applied transverse fields. The spin noise peak moves with the expected g-factor of ~-0.41, and the width gives the spin lifetime.

However, recent advances in digitizer technology and computational power have made it possible to implement a all-digital 'desktop' approach to real-time spectral analysis in the RF domain, such that *all* the incoming data is processed and analyzed. We have put together a real-time RF spectrum analyzer using a fast (400 million samples/second) 12-bit digitizer that continually streams data over a fast PCI-X bus to a multi-core Intel workstation, which breaks the datastream into records of length 2048 and performs parallel FFTs in real time. Using this system, we are now able to achieve extremely (and suitably) low noise floors after only a few minutes of averaging (compared with >5 hours using a commercial system). In this way we directly observe the spin fluctuations of free electrons in GaAs (see Fig. 1). At the present time we are directly comparing the noise linewidths with the electron spin lifetimes that we measure by independent Hanle-effect means, as a function of temperature, laser wavelength, and electron density.

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[1] S. A. Crooker *et al.*,Nature **431**, 49 (2004) ; M. Oestreich *et al*, PRL **95**, 216603 (2005).