Force-Detected Nuclear Magnetic Resonance of Unstrained Gallium Arsenide with Applications to the Development of Spintronic Devices

Lee E. Harrell
Department of Physics
U.S. Military Academy, West Point, NY

Doran D. Smith
Sensors and Electron Devices Directorate
U.S. Army Research Laboratory
Adelphi, MD

1 Executive Summary

Spintronics devices (i.e. devices that exploit the spin degree of freedom of the electron instead of, or in addition to, its charge) have already impacted technologies relevant to the Army, increasing hard drive capacity from 1 G to 20 G in a single step. Fast, high-density, low-power, nonvolatile computer memory based on spintronic devices will soon be competitive with conventional computer memory giving us zero boot time computers. Even more exciting is the possibility of dynamically configurable microprocessors based on programmable spintronic devices. However, to fully realize the potential of the spin degree of freedom of the electron, carriers must be able to travel large distances and through a series of material interfaces while preserving both spin-orientation and phase information. Control of phase coherence is also important if spintronics technology hopes to deliver devices useful for quantum computing.

Methods for detecting the net effects of electron transport through complete devices have been demonstrated. However, these methods shed little light on the electron dynamics inside the device. Transit times for individual electrons make real-time, three-dimensional imaging of the inner workings of devices impractical, but in GaAs-based semiconductors, spin-polarized currents leave an impression in the nuclear spin lattice that persists over a period of about 20 minutes. We have been developing force-detected nuclear magnetic resonance (NMR) technology to image the resulting nuclear spin polarization in order to learn more about the dynamics of electron spins in these materials.

Our recent efforts have focused on refining our experimental techniques, identifying sources of experimental noise and developing our understanding of the signals from a test sample of unstrained GaAs. Both a narrow bulk peak and “slice” data, which represent a one-dimensional image of the nuclear polarization beneath the probe, have been observed for the case of thermal polarization of the nuclear lattice in a 5.2-T applied magnetic field at a temperature of 4.2 K (nominal). In the near future, we expect to replace the GaAs test sample with functioning spintronic devices.

2 Introduction

This report details recent efforts and results in our long-term effort to learn about the transport of spin-polarized electron currents in GaAs-based semiconductor heterostructures through magnetic resonance imaging of the nuclear spin lattice using magnetic resonance force microscopy (MRFM). The connection between the spin-polarized current and the magnetization of the nuclear lattice is a process called dynamic nuclear polarization (DNP). DNP arises because a steady-state current of spin-polarized electrons in a non-magnetic material entails a non-equilibrium distribution of electron spins. If the nuclear lattice starts out in thermal equilibrium, there will be a net transfer of angular momentum from the electrons to the nuclei. This transfer is facilitated by the presence of shallow acceptor states in the material that enhance the coupling between the conduction electrons and the nuclear spins.

As a GaAs-based spintronic device operates, nuclear polarization in the regions carrying the spin-polarized current increases above the thermal equilibrium value. When the current is interrupted, the nuclear lattice becomes largely decoupled from its environment and the pattern of excess nuclear polarization in regions that experienced spin-polarized electron current persists, in the case of GaAs, for about 20 minutes. By measuring the nuclear spin polarization using magnetic resonance imaging we will observe the path of the spin currents in the device and the effect of specific device structures on the electron spin.

3 Body

MRFM is a scanned-probe microscopy based on force-detected NMR as illustrated in Figure 1. In this case, the sample is mounted on a micromachined cantilever, typically several hundred microns in length, in the presence of a large applied magnetic field and a magnetic field gradient arising from a near-by magnetic particle. The magnetic field gradient exerts a force on the magnetized sample resulting in a displacement of the cantilever. The force due to a particular nuclear isotope can be isolated using NMR radio frequency (RF) techniques to cyclically invert the direction of the nuclear magnetic moment at a frequency f_d. The signal from the isotope of interest then appears as a driven oscillation of the cantilever. The presence of the magnetic field gradient makes the NMR resonance condition position dependent, so it possible to cycle the magnetic moments at only select locations within a sensitive slice of the sample. Such spatial dependence makes three dimensional magnetic resonance imaging of the sample possible, as has been demonstrated by Wago [1] and Zuger [2].

The loaded cantilever is a mechanical resonator with frequency f_c and quality factor Q. The amplitude A of the cantilever response will depend on both the amplitude and frequency of the driving force, f_d. For f_d well bellow f_c, the cantilever response is in phase with the driving force F and the amplitude is essentially the zero-frequency response, $A = F/k$, where k is the spring constant of the cantilever. When driven on resonance ($f_d = f_c$), the cantilever response lags the driving force by $\pi/2$ rad and its amplitude is enhanced by a factor of Q. MRFM experiments are typically carried out with $f_d = f_c$, to take advantage of the Q enhancement of the signal.

The amplitude of the force signal is obtained by integrating the magnetic dipole-gradient force over the volume V where the sensitive slice intersects the sample:

$$F_z = \iiint_V n\langle \mu_z \rangle \frac{\partial B_z}{\partial z} dV \tag{1}$$

where n is the number density of the observed isotope in the sample and B_z is the z-component of the total static magnetic field. The magnetic field gradient can be calculated from the known geometry and magnetic properties of the gradient source. The sensitive slice is the locus of points within the sample where the total static magnetic field is related to the angular frequency of the RF irradiation by $\omega_{RF} = \gamma B_0$. The force signal is proportional to the average sample magnetization in the sensitive slice, making determination of the nuclear spin polarization practical.

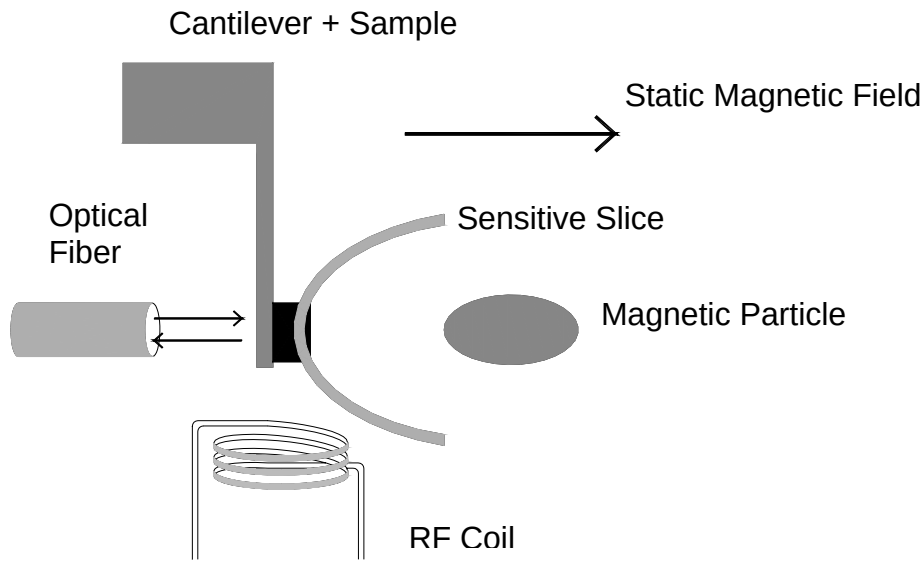

Figure 1. Diagram of a magnet-on-cantilever force-detected NMR experiment.

Proposed in 1991, and first demonstrated in 1992, MRFM is a relatively immature imaging technique[3]. Any attempt to use it in practical and quantitative measurement is an ambitious undertaking. As a result, we have taken a methodical approach to implementing the necessary technology. Our earliest work in low-temperature MRFM was on the test sample CaF_2[4], which had been studied in detail by others[5]. This allowed us to learn low-temperature MRFM techniques without the technical risk of working with a sample that was unsuitable.

Having obtained a working MRFM signal from the CaF_2 sample, we turn to searching for an MRFM signal in GaAs. This task was complicated by a lack of knowledge of the relevant NMR time scales for the sample. Using a probe similar to that used in the CaF_2 work, we were able to isolate an MRFM signal for each of the three naturally occurring isotopes in GaAs[6]. In the process, we determined the spin-relaxation time of the sample to be about 20 minutes. This turns out to be a particularly convenient relaxation time because the sample reaches thermal equilibrium on laboratory time scales, yet spin-polarization patterns persist long enough to be observed with tolerable signal-to-noise ratios. We were also able to demonstrate the practicality of imaging spin polarization contrast by using NMR techniques to first pattern and then image the nuclear spin polarization in one dimension.

After our successful initial experiments with thermally polarized GaAs we explored the effects of DNP on the MRFM signals. In this case, we produced the non-equilibrium electron spin populating by illuminating the sample with circularly polarized light, rather than by passing a spin polarized current through it. Through DNP enhancement of the nuclear spin polarization, we were able to increase the overall MRFM signal by a factor of 12, reduce our sensitive slice thickness to 170 nm and improve our slice resolution to 500 nm[7].

Our latest work has been to construct and test a new MRFM probe that allows us to obtain MRFM data with the magnetic gradient particle, rather than the sample, mounted on the force-sensing cantilever. By Newton's third law, one should measure the same force regardless of whether the sample or the magnetic particle is mounted on the cantilever. However magnet-on-cantilever MRFM is more technically challenging because of the potential for the magnetic moment of the magnetic particle to interact with the DC background magnetic field, the RF magnetic field, and heating of the cantilever by RF-induced eddy currents in the magnetic particle. Nonetheless, this change is necessary because it is impossible to mount an operating spintronic device on the end of a microcantilever without spoiling its mechanical properties.

Our initial tests with the new probe were conducted on a thin layer of GaAs under conditions of thermal polarization. Though we observed an MRFM signal, the shape of the signal as a function of applied magnetic field did not match the predictions of models based on equation (1). Based on our understanding of the experimental geometry and the sample, the signal was too small, and the width of the bulk peak, the signal from areas of the sample well away from the magnetic particle, was larger than expected. The most recent tests have shown that the anomalous width of the bulk peak was due to mechanical strain in the sample. With improved mounting techniques, the bulk peak is now observed to be narrower than the resolution of the instrument and the overall shape of the cantilever response vs. magnetic field curve agrees with our model predictions. However, the magnitude of the signal is still a factor of 2 smaller than we expect. While troubling, this factor is not likely to prevent us from imaging nuclear spin polarization, and we expect to understand it better as we gain experience with the probe.

Now that we have obtained baseline data from the new probe under experimental conditions similar to what we expect to use with actual devices, we are currently focusing on an end-to-end assessment of the performance of our probe. We are particularly interested in identifying and reducing any source of noise that exceeds the fundamental thermomechanical limit to the force sensitivity of our cantilever. Extraneous noise sources in our system are either mechanical or electronic. Mechanical noise actually shakes the cantilever, and is thereby added directly to the MRFM signal. Examples include building vibration, optical back action of the interferometer that is used to detect the vibrations of the cantilever and electronic noise in the circuits that control piezoelectric positioning elements in the probe head. Electronic noise comes primarily from the interferometer laser power supply and the photodiode detection and amplification circuitry that monitors the interferometer output. Once this assessment is complete, we expect to transition to the study of actual spintronic devices.

4 Conclusion

We have documented significant progress in our efforts to image spin polarized currents in spintronic devices. Major milestones include the observation of the first MRFM signal from GaAs, high-resolution one-dimensional imaging of nuclear spin polarization, observation of

DNP-enhanced MRFM signals in GaAs, and detection of MRFM signals in unstrained GaAs using magnet-on-cantilever MRFM techniques. We have a quantitative understanding of the shape of our signal as a function of applied magnetic field and are working towards a complete quantitative understanding of the magnitude of the signal. Current work involves the identification and elimination of spurious noise sources and we expect to move on to tests on spintronic devices in the near future.

References

[1] K. Wago, D. Botkin, C. S. Yannoni, and D. Rugar, "Paramagnetic and ferromagnetic resonance imaging with a tip-on-cantilever magnetic resonance force microscope," *Appl. Phys. Lett.* **72**, 2757 (1998).

[2] O. Zuger, S. T. Hoen, C. S. Yannoni, and D. Rugar, "Three-dimensional imaging with a nuclear magnetic resonance force microscope," *J. Appl. Phys.* **79**, 1881 (1996).

[3] J. A. Sidles, J. L. Garbini, K. L. Bruland, D. Rugar, O. Zuger, S. Hoen, and C. S. Yannoni, "Magnetic resonance force microscopy," *Rev. Mod. Phys.* **67**, 249 (1995).

[4] Doran D. Smith, John A. Marohn and Lee. E. Harrell, "Detailed description of a compact cryogenic magnetic resonance force microscope," *Rev. Sci. Instrum.* **72**, 2080 (2001).

[5]K. Wago, O. Zuger, R. Kendrick, C. S. Yannoni, and D. Rugar, "Low-temperature magnetic resonance force detection," *J. Vac. Sci. Technol. B* **14**, 1197 (1996).

[6] Kent R. Thurber, Lee E. Harrell, Raúl Fainchtein and Doran D. Smith, "Spin polarization contrast observed in GaAs by force-detected nuclear magnetic resonance," Appl. Phys. Lett. 80, 1794 (2002).

[7] Kent R. Thurber, Lee E. Harrell and Doran D. Smith, "170nm nuclear magnetic resonance imaging using magnetic resonance force microscopy," J. Mag. Reson. **162**, 336 (2003).