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EPR: Progress towards spin-based quantum computing

Electron- and/or nuclear-spin-based quantum computing requires the control and measurement of a very small number of spins, ideally just one. Spin-dependent recombination (SDR)[1-4] is an electron paramagnetic resonance (EPR) technique that is potentially useful in spin-based quantum computing.[5] It is orders of magnitude more sensitive than conventional EPR and permits magnetic resonance measurements on the fundamental building blocks of modern microelectronics: metal oxide silicon field effect transistors (MOSFETs). SDR-detected magnetic resonance applied to an array of MOSFET-like devices may have particular promise in quantum computing because the response can be turned on and off at specific sites via application of voltage.[5] In fact, a leading spin-based quantum computer proposal is based upon an exotic MOS system.[6]

Figure 1. A 'quasi-optical' electron paramagnetic resonance (EPR) spectrometer.

At 'modest' magnetic-field strength, the sensitivity of SDR is often, to zero-order, field independent.[1-5] However, since SDR involves the polarization of charge carriers and deep-level spin systems, very-high-field SDR should provide additional high-sensitivity advantages. This could eventually allow for single-spin detection, because the high fields greatly increase polarization. However, at very-high fields and frequencies, the conventional microwave approaches (microwave waveguides, conventional cavities, etc.) become essentially impossible as the wavelengths of the electromagnetic irradiation—and consequently the dimensions of the microwave cavities and waveguides—extend from microwave dimensions (~cm) to far-infrared dimensions (~mm or less).

Recently, 'quasi-optical' approaches have been shown to have great promise for conventional EPR at extremely high fields.[7] Here we report on high-sensitivity SDR measurements using a 'quasi-optical' spectrometer. These preliminary high-field measurements were made under circumstances very far from those that would yield optimal sensitivity. Several clearly-possible modifications of our initial measurements should each yield improvements of one to several orders of magnitude: thus, our results strongly suggest that (fairly rapid) single paramagnetic site detection will be possible with high-field SDR.

The experiment

At the National High Magnetic Fields Laboratory we made SDR-detected EPR measurements using SiC MOSFETs. These were configured as gate-controlled diodes with gate areas of 100μm×100μm and measured using a high field 'quasi-optical' EPR spectrometer. The frequency we used was 110GHz: the resonance appeared at 4.26 Tesla. The 'quasi-optical' system is shown in Figure 1, and is described in detail elsewhere.[7] A representative SDR trace (200s acquisition time) is illustrated in Figure 2. The signal-to-noise ratio is approximately 120, and the full width at half maximum of the (essentially Gaussian) line shape is 26 Gauss, yielding a sensitivity of about 4×10^4 spins/Gauss. This sensitivity was: achieved at room temperature, at quite low B1 (the resonance frequency field), without significant signal averaging, and at considerably less than the highest-possible fields that can be achieved.

Although a direct extrapolation of response is not possible, a comparison of SDR amplitude versus power at low and high field strengths is shown in Figure 3. This suggests that a large improvement in high-field sensitivity will be achieved by increasing B1. The low-field measurements were carried out us-

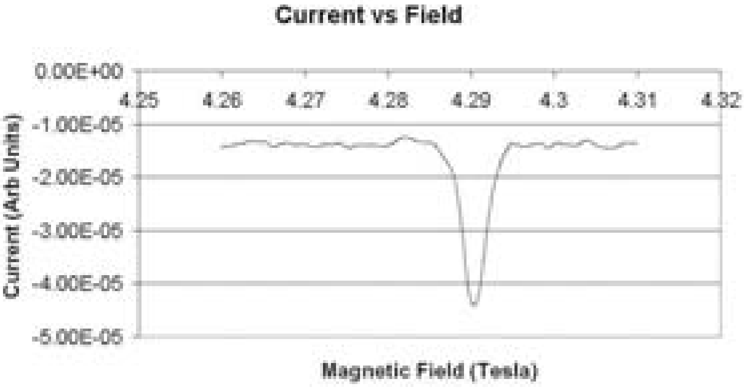

Figure 2. A representative spin-dependent recombination (SDR) trace.

ing a 150mW microwave source and a TE102 microwave cavity with a loaded quality factor of about 5000. The polarization in our preliminary room-temperature measurements was less than 2%. Lower temperatures and even-higher fields will allow for a several orders of magnitude boost in the ratio of magnetic field to absolute temperature, permitting essentially-complete polarization of the charge carrier and the deep-level spin systems. The increased polarization will yield a large, if difficult to precisely quantify, increase in sensitivity.[1-3,5] Although long-signal averaging is of questionable utility in quantum computing applications, it is worth noting that the practical limit for signal averaging is at least a day. Signal averaging for a day would increase sensitivity by about a factor of 20.

Since several fairly straightforward modifications of our measurements will each likely provide one to several orders of magnitude increase in sensitivity, our results strongly suggest that fairly-rapid single-spin detection will be possible via high-field quasi-optical SDR detected EPR. This sensitivity will be possible in MOS integrated circuits in which individual transistor spin sites may be rendered addressable via application of gate and source-drain bias. A very-recent study argues that somewhat similar high-field electrically-detected magnetic-resonance measurements (involving extensive periods of data acquisition) have produced single paramagnetic site sensitivity in a MOSFET.[8]

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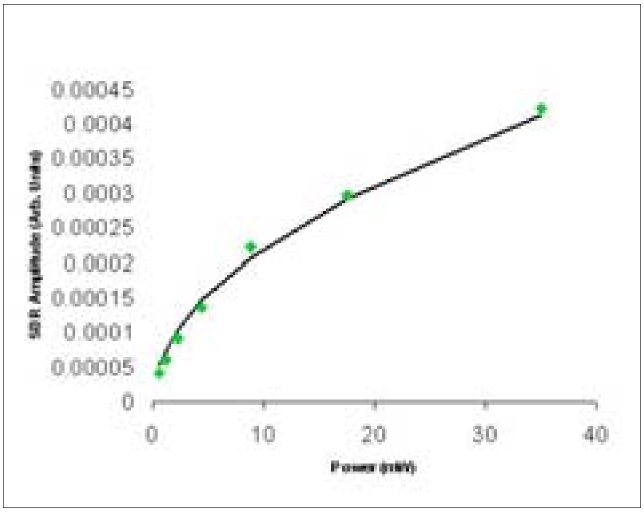

Figure 3a. SDR amplitude versus power at high field (4.26 Tesla), low power, and no resonant cavity.

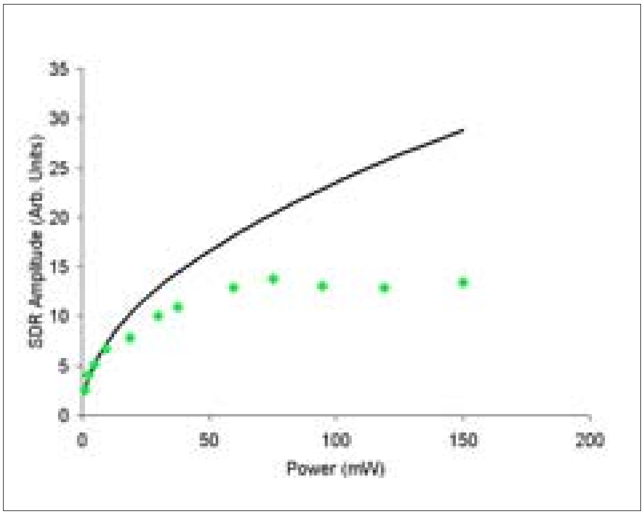

Figure 3b. SDR amplitude versus power at low field (~1/3 Tesla), high power, and up to 150mW applied to a Q 5000 TE102 cavity.