Proceedings of the 3rd IEEE Int. Conf. on
Nano/Micro Engineered and Molecular Systems
January 6-9, 2008, Sanya, China

Theoretical Analysis of Single Electron Spin Surface Detections

Frank X. Li*, *Member, IEEE*, M. Tabib-Azar, *Senior Member, IEEE* , J. Adin Mann

***Abstract*— the ultimate spintronic devices based on electron spins will utilize a single electron as one quantum bit, thus spatial detections of a single electron become essential. This paper presents a theoretical analysis of the unpaired single electron spin detection with considerations of spin noises and coherent spontaneous emissions. The classic electron spin resonance spectrometer uses a high Q-factor tuned microwave cavity, which is capable of detecting the free electron spin density in the range from 10^6 to 10^{11} spins. The key for single electron spin detection relies on the detections of the energy exchange between the electron and microwave virtual photons. Furthermore, for such a tiny energy, the free induction decay signal will be overwhelmed by the surrounding noises. The possibility of increasing the sensitivity of the ESR spectrometer to one single spin using magnetic field modulation is presented.**

***Index Terms*— electron spin resonance, spin noise, atomic force microscopy**

I. BACKGROUND

ONE of the intrinsic properties of electron, the spin angular momentum is part of the modern quantum physics foundations. To pinpoint the single electron locations on the sample surface, the first obstacle is how to detect the presence of a single electron. The electron intrinsic spin property generates a weak magnetic dipole. However, the detection of this electron magnetic dipole is not as easy as detecting that of a large bar magnet, for example. As indicated in Fig. 1, the rotation of a large bar magnet can be easily observed by measuring the induced voltage across an induction coil based on Faradays' law, which can be expressed as,

$$V = -N \cdot \frac{d\Phi}{dt} . \qquad (1)$$

Assuming a 10-turn coil with an area of 0.1 cm^2 and the magnetic flux changing rate, $d\Phi/dt$, is 10 mT/sec, the induced EMF voltage V is ~100 μV. The current, reliable low-voltage measurement equipment detects 100 pV accurately and the theoretical minimum measurable magnetic field changing rate is 10 nT/sec. The magnetic field of the electron along any given axis is very difficult to measure. However, the magnetic dipole moment of the electron is considered as one of the fundamental physical constants, which is given as 9.27×10^{-24} J/T by the NIST database. For a large bar magnet, by comparison, the magnetic dipole moment is close to 1 J/T. Since the magnetic field generated by the magnetic dipole is proportional to the magnetic dipole moment, the magnetic field changing rate for flipping of an electron is much smaller than that of a small bar magnet. If the same 10 turns coil is used, the induced voltage for a single electron is too tiny to detect by any existing voltage measurement equipment [1-3].

The free electron tends to align its magnetic dipole moment with

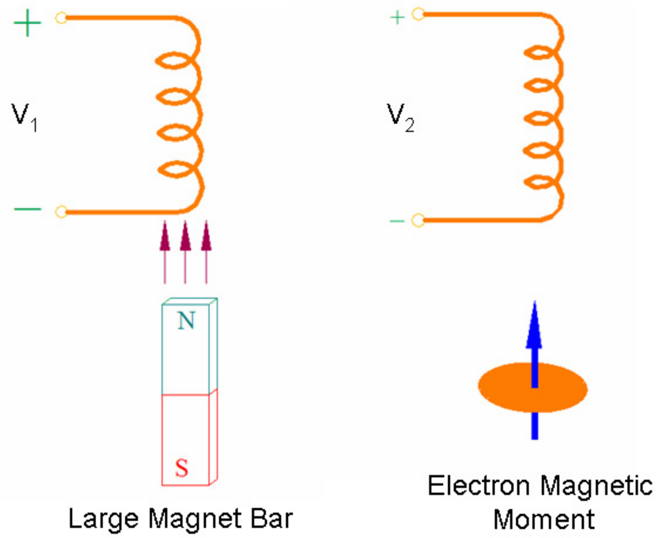

Fig. 1. The EMF induced by the rotation of large magnet bar can be detected through high sensitive voltage meter. Similarly, the change of single electron dipole moment induces EMF, however, it is too difficult to detect due to the small magnitude.

Manuscript received September 1, 2007.

*Contacting Author: Frank X. Li is with the Electrical and Computer Engineering Department, Youngstown State University, Youngstown, OH 44555 USA (phone: 1-330-941-2253; fax: 1-330-941-3381; email: xli@ysu.edu).

978-1-4244-1908-1/08/$25.00 ©2008 IEEE.

the external magnetic field and the energy splits into two different energy levels. Assume the external field is along the z axis, the two energy levels differ in energy by $2\mu_z B$, where the μ_z is the magnetic dipole moment of a single electron, and B is the external magnetic field. If an alternating magnetic field with source frequency satisfy,

$$hf = 2\mu_z B \tag{2}$$

where h is the Planck constant, f is the frequency, the electron with the lower energy level can reverse its magnetic dipole moment to $-\mu_z$ [4]. The spin-flipped electron will soon drop down to its lower energy level by emitting a photon with the same amount energy hf. The electron will continue the process of spin flipping as long as the alternating magnetic field satisfies Eq. 2. This resonant condition is called the electron spin resonance (ESR) or electron paramagnetic resonance (EPR). Therefore, an alternative way to detect the presence of one single electron is to measure the electron power absorptions under spin resonance conditions. This paper presents the theoretical requirement of one single electron detection at microwave frequencies.

II. THEORETICAL ANALYSIS

A. *The challenge of background noises*

Under magnetic resonance conditions, the single electron consumes power of 8.24×10^{-16} W to sustain the electron spin resonance at 3.7 GHz with spontaneous emission. Since an object with a physical temperature above absolute zero radiates finite energy, the Johnson noise power for the probe is,

$$P_r = kT_A \Delta f \tag{3}$$

where the k is the Boltzmann's constant, T_A is the probe temperature (K) and Δf is the bandwidth. At room temperature, for a probe operating at 3.7 GHz with 0.1 GHz bandwidth, the noise power is around 4.14×10^{-13} W. Even if the measuring equipment is capable of detect the power level at 10^{-16} W, for measurement taken at room temperature, the noise will cover the ESR signal totally.

B. *The classic electron magnetic resonance setup*

The classic electron spin resonance detection is shown in Fig. 2. A large electromagnet provides a homogenous magnetic field that degenerate the electron energy levels. The microwave source supplies microwave photons, which are absorbed by the low energy level electrons under resonant conditions. The circulator isolates the incoming and reflected microwave signal to make certain that the crystal detector converts only the reflected microwave energy to a voltage signal. The phase sensitive detector suppresses the background noise and amplifies the electron spin resonance signals.

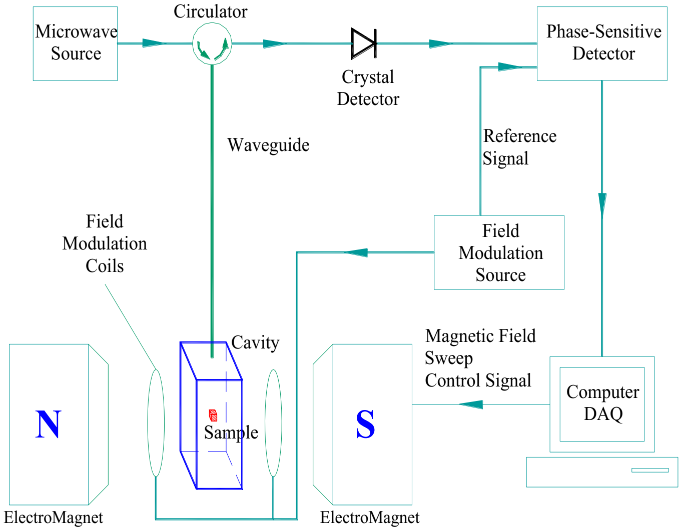

Fig. 2. The classic electron-spin resonance detections setup with a microwave cavity as the resonator. A phase sensitive detector is used to suppress background noise. The signal is analyzed to derive the number of free electron spins in the sample and the relaxation time of the spins.

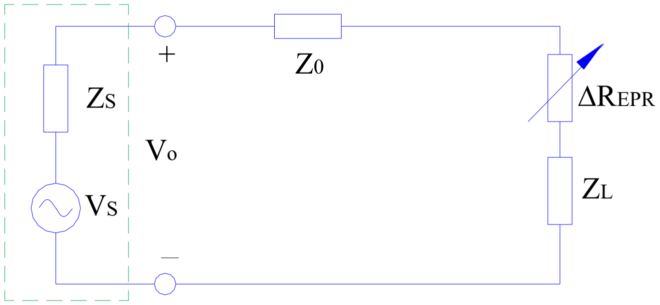

Fig. 3. The equivalent circuit of an electron spin resonance system is composed of, the microwave source, transmission line and Resonance load. Under the resonant condition, the load impedance matches the transmission line perfectly. The additional resistance ΔR_{EPR} represents the electron spin resonant power absorptions.

At microwave frequencies, the equivalent Parallel LC resonator is a completely enclosed rectangular or cylindrical metal box, which is also called the microwave cavity. It is designed as an energy storage device with Q factor in the range of 3,000 to 5,000 or higher, which makes it a very good EPR resonator to amplify weak ESR signals. As shown in Fig. 3, the microwave circuit is tuned to have perfect matches between the load and the transmission line. Under resonant condition, the reflected power from the cavity is at the minimum, and the slight change of the electron resonance power absorption changes the system Q factor dramatically and a large amount of microwave power reflects through the circulator port. The reflect power is exactly equal to the power absorption due to microwave photon absorption. The signal is then amplified and collected through computer data acquisition system for further analysis.

C. The magnetic field modulation and single electron magnetic resonance power absorption line shapes

Two different approaches are available for obtaining the ESR signal with higher signal to noise ratio, one is the magnetic field modulation and the other is the frequency modulation. For the magnetic field modulation, the amplitude of the modulation should be less than the ESR power absorption line width. For a given resonator, the frequency modulation not only changes the electron spin resonance power absorption levels, but also changes the characteristics of the resonator. Therefore, the magnetic field modulation is the preferred method. It is practical to use the biasing magnetic field sweeping step as the modulation amplitude, for instance, if the linear magnetic field is sweeping at one Gauss per step, the modulation amplitude should be at one Gauss or more. Therefore the instantaneous magnetic field at any moment can be written as:

$$H(t) = H_0 + \delta H_s(t) + H_m \cos(\omega_m t) \qquad (4)$$

Where $H(t)$ is the total magnetic field at time instance t. The scanning magnetic field $\delta H_s(t) = C_1 \cdot t$ and C_1 is the magnetic field scanning rate (Gauss/sec.), which is much slower than the sinusoid component $H_m \cos(\omega_m t)$. The term $H_0 + \delta H_s(t)$ can be treated as a constant of the sample at any time instances during the scanning process. By superposing another low frequency alternating magnetic field H_m on the external magnetic field, the absorption power changes at the same frequency as H_m changes. The magnitude of the modulation magnetic field is very small compare to the main magnetic field, thus, the total magnetic field at any give moments is still homogeneous. Additionally, the frequency of the modulating field can be precisely controlled and identical synchronization signals can be generated for phase-sensitive amplifiers.

The electron spin resonance power absorption line shapes are similar to the Gaussian and Lorentz distributions and the theoretical line shape is a Voigt function, which is a linear combination of the Gaussian and Lorentz functions. The actual detected signals are first derivatives of the power absorption line shapes. The theoretical first derivate of the ESR absorption line shape is shown in Fig.4. The peak ESR power absorption is at the zero crossing magnetic field and the two peaks correspond to the largest power absorption line slopes. The signal can be integrated to obtain the actual power absorption line shapes.

D. The surface electron detection resonators

To obtain the spatial locations of the free electron, an open

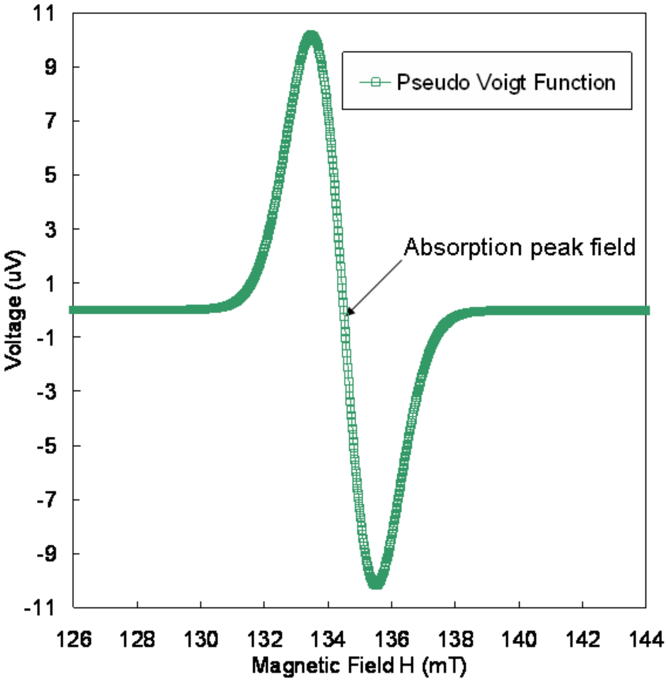

Fig. 4. The theoretical ESR absorption line shape is a Voigt function, which is a superposition of independent Lorentz and Doppler line broadening mechanisms. The voltage peaks shown in above figure are at 10 μV, for the single electron detection, the noise floor must be reduced below the signal amplitudes.

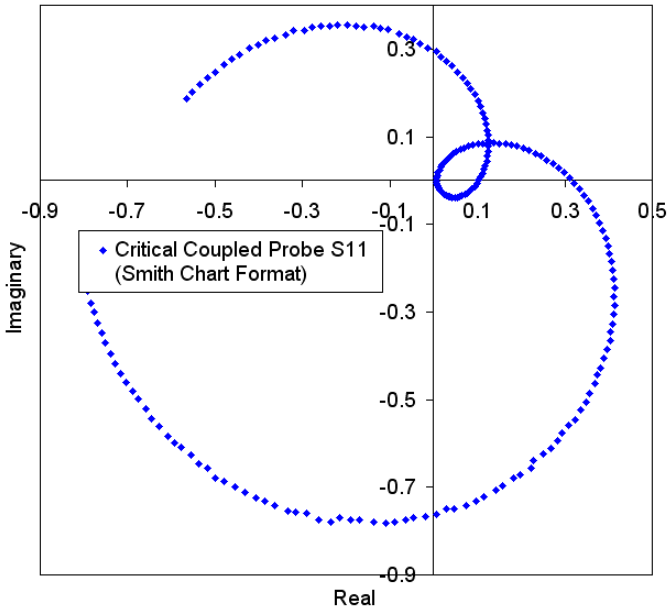

Fig. 5. The smith chart shows the impedance of the probe at the operating frequency range in one of experiments. The stability of the coupling between the probe and the microwave source is crucial during the unpaired electron detection.

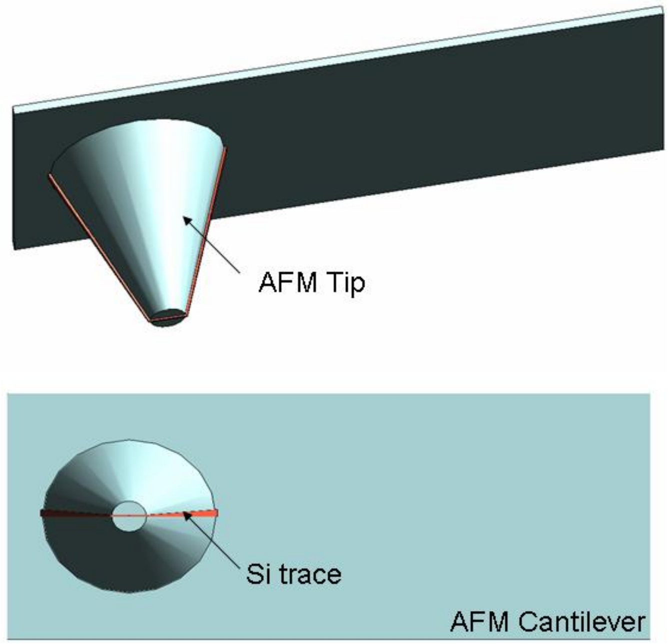

Fig. 6. AFM probe tip provides an excellent platform for microwave dipole probes. As illustrated in the figure, the thin trace of silicon will be etched on the special glass AFM tips to conduct microwave current, which generates the alternative magnetic field that will be used to interact with the unpaired electrons.

structure magnetic dipole probe was constructed to not only detect the number of electron spins, but also provides the spatial information by tracking the tip of the probe. The S_{11} plot of the system is shown in the smith chart format of Fig. 5. Each point on the smith chart plot represents the impedance at a certain frequency. The related frequency near the zero crossing is chosen as the operating frequency of the probe. Another alternative for measuring the ESR signal is through the electric dipole probe, which uses the alternating electric field as the sensing field and the sensitivity is around 10^{11} spins [5].

In our approaches, typical crystal detectors, such as Agilent 8473 series are used and the sensitivity is 0.5 mV/μW. Our experiments proved that using such crystal detectors, a 1000x preamplifier and a lock-in amplifier, the noise floor can be reduced to 0.02 nW and the minimum detectable electrons are around 200,000 spins [6-7].

E. The theoretical single electron detection

For single electron detections, the detection of 8.24×10^{-16} W at 3.7 GHz is very challenging. The electron resonance signal must be amplified to around 1 μV, such that the lock-in amplifier can detect the single electron power absorption during resonance. Furthermore, the noise floor needs to be reduced to a level below 9.2×10^{-15} W. There are many different ways to increase the sensitivities of the system and increase the signal to noise ratios. One way is to increase the operating frequency of the system, such that the single electron consumes higher power under electron spin resonance conditions. The noise floor can be reduced further by reducing the size of the probe tip. The probe system can be enclosed in a shielded container that will help further reduce environment noises. The proposed equipment for single electron spin detection is shown in Fig. 6, where the microwave magnetic dipole probe is integrated on the AFM tip. The atomic force microscopy (AFM) techniques are widely used in sample topographic imaging process and the AFM tip is an excellent tool for recording the locations of the free unpaired electrons. Different shapes of the AFM tips can be manufactured to find the highest Q factors. The small scale Silicon trace etched on the top of AFM tips is an excellent conductor for microwave frequency, thus reducing the resistive losses of the probe.

III. CONCLUSIONS

For single electron spin detection, an AFM integrated microwave probe is presented. The proposed device will have higher system Q factor, lower background noises and higher operating frequencies. Additionally, the future sensitivity improvement of measurement equipment will also facilitate reaching the goal of single electron surface detection.

REFERENCES

[1] D. I. Hoult, N. S. Ginsberg, "The Quantum Origins of the Free Induction Decay Signal", *Journal of Magnetic Resonance* 148, pp. 182–199, 2001

[2] D. I. Hoult , B. Bhakar, "NMR signal reception: virtual photons and coherent spontaneous emission", Magnetic Resonance: an Educational Journal archive, Vol. 9 , Issue 5, pp. 277-297, 1997

[3] R. H. Dicke, ''Coherence in Spontaneous Radiation Processes,'' *Physics Review*, Vol. 93, pp. 99-110, 1954

[4] C. P. Poole, Jr. and H. A. Farach, "Handbook of Electron Spin Resonance Vol. 2" Springer-Verlag New York, Inc., NY, 1999, ISBN 1-56396-044-3

[5] F. Sakran, A. Copty; M, Golosovsky, N. Bontemps, D. Davidov, D.A. Frenkel, "Electron spin resonance microscopic surface imaging using a microwave scanning probe," *Applied Physics Letter* 82 (9): pp. 1479-1481 Mar. 2003.

[6] F. Li, M. Tabib-Azar, J. Adin Mann, "Surface Electron Spin Resonance Study on Ruby Crystal Using Evanescent Microwave Microscopy Techniques", *IEEE Sensors Journal*, Vol. 7, Issue 2, pp. 184-191, Feb. 2007

[7] F. Li, J. A. Mann, Jr., M. Tabib-Azar, "A near-field microwave microscope and electron spin resonance detection on ruby crystal surface," *Applied Optics* Vol. 45(10), pp. 2191-2198, 2006.