Near Zero Field Magnetoresistance Spectroscopy: A New Tool in Semiconductor Reliability Physics

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***Abstract*— A relatively simple addition to many widely utilized semiconductor device characterization techniques can allow one to identify much of the atomic scale structure of point defects which play important roles in the electronic properties of the devices under study. This simple addition can also open up the possible exploration of the kinetics involved in some reliability phenomena as well as in multiple transport mechanisms. This addition is a small (0 to a few mT) time varying magnetic field centered upon zero field. A readily observable difference between various device responses at zero and small fields can be observed in a wide range of measurements often used in semiconductor device characterization. These measurements include metal-oxide-semiconductor field-effect transistor (MOSFET) charge pumping, metal-oxide-semiconductor (MOS) gated diode recombination current, so called direct current current-voltage (DCIV) measurements, deep level transient spectroscopy, and simple current measurements in dielectric films and in pn junctions. Multiple materials systems of great technological interest can be explored with the techniques. They are based on near zero field magnetoresistance (NZFMR) phenomena, spin-based quantum effects involving magnetic field induced changes which occur in multiple electronic transport phenomena. Because these spin-based changes are strongly affected by fundamentally well understood spin-spin interactions such as electron-nuclear hyperfine interactions or electron-electron dipolar interactions, this NZFMR response has quite substantial analytical power. The NZFMR techniques can be gainfully applied to device structures based upon numerous materials systems, among them being silicon dioxide, silicon, silicon carbide, silicon nitride and amorphous SiOC:H films utilized in interlayer dielectrics.**

***Index Terms*—MOSFETs, reliability**

I. INTRODUCTION

Great progress has been made in the development of an atomic scale understanding of the physical mechanisms involved in many semiconductor device reliability issues. Many of these issues involve metal/ oxide/semiconductor field effect transistors (MOSFETs). Such fundamental atomic scale understanding is arguably key to both the amelioration of these issues and to the development of reliable physically based models which allow the prediction of device lifetime from the extrapolations involved in accelerated stressing studies. Although quite sophisticated purely "electronic" measurements have long been widely available for such studies, direct investigation of the physical and chemical nature of the atomic scale mechanisms involved [1] has been almost exclusively limited to electron paramagnetic resonance (EPR) [2] and electrically detected magnetic resonance (EDMR) [3]. EDMR is EPR detection via electronic measurements. EPR and the related EDMR techniques are quite powerful but require complex and quite expensive apparatus. The apparatus typically includes large, relatively expensive electromagnets with precise and extremely stable magnetic field control, microwave generators, and microwave cavities with fairly extensive associated detection electronics. The cost of such systems is substantial and overall power requirements are often in the range of several kilowatts. The cost and complexity of magnetic resonance apparatus has almost certainly limited the wide application of these techniques, especially within industrial reliability physics research and development laboratories. The EDMR and EPR measurements are also of little use in studies of fully packaged devices, since even modest frequency electromagnetic radiation can be absorbed by metallization around the devices under study.

If apparatus with much of the analytical power of EPR and EDMR were to be widely available at relatively little cost through modest modification of equipment already widely utilized in reliability physics laboratories, we believe that it would likely be widely utilized in the industry and that this utilization would have a significant impact on the development of reliability physics. In this work we show how near zero field magnetoresistance (NZFMR) [4],[5],[6],[7],[8] can be simply added to multiple device characterization systems and illustrate how the results obtained from such apparatus can yield an atomic scale understanding of imperfections which deleteriously affect device performance and reliability.

II. UNDERLYING PHYSICAL PRINCIPLES

Two NZFMR phenomena are utilized in this work: the spin dependent nature of charge capture and spin dependent nature of trap-to-trap tunneling. The basic idea behind the response can be qualitatively understood on a very rudimentary level in terms of fairly basic semiconductor physics. First consider a trap to trap tunneling event. Specifically consider tunneling between two "dangling bond" defects, and that each of the two dangling bond defects is initially occupied with one unpaired electron. Suppose that the unpaired electrons in both dangling bonds have the same spin quantum number. If this is the case, tunneling of the electron from site a to site b is a forbidden event because, as the Pauli exclusion principle indicates, two spins with the same spin quantum number cannot occupy the same dangling bond orbital. Now suppose that the unpaired electrons have opposite quantum numbers. In this case the tunneling event is allowed.

Suppose now that we consider a system in which many of these potentially allowed or forbidden tunneling events are possible. How can it be that the application of a small magnetic field could change the observed tunneling current? As a first approximation, consider only the energy involved with the electron magnetic moments interacting with the applied magnetic field. Thus, we assume that the unpaired electron spins are not affected by the local dangling bond environments. Remember that electrons have magnetic moments and that the energy of a magnetic moment $\boldsymbol{\mu}$ within a static magnetic field B is given by $-\boldsymbol{\mu}\cdot\mathbf{B}$. Thus, the contribution to energy from the magnetic field interaction energy of the two dangling bond electron system, the two-spin system in which both electrons have the same spin quantum number, would scale with the size of the applied magnetic field vector **B** and have a value of zero only at applied field zero. However, in the case in which the two spins have opposite quantum numbers, the energy due to the magnetic field interaction would be zero, no matter what the applied field. Quantum mechanics tells us that in the case of such a two-state system, when two states have the same energy, they can mix [4],[5],[6],[7],[8]. With both states simultaneously present at zero field then, the previously forbidden tunneling event involving unpaired electrons at sites a and b with the same spin quantum numbers can become allowed. Thus, if we are measuring, for example, a leakage current in a dielectric film due to trap to trap tunneling, we would expect to see an increase in current if the applied field is adjusted from some finite value to zero. We call this response NZFMR.

A somewhat analogous NZFMR response can occur in electron and or hole capture; this response can be readily observed in currents dominated by electron-hole recombination in indirect band gap semiconductors such as silicon [7],[8]. It can also be observed through changes in current transients involving single charge trapping events. Consider the case of recombination current in an indirect band gap semiconductor. As is the case for NZFMR in trap to trap tunneling, a rudimentary understanding can be gleaned from a similar very simple model. Imagine a conduction electron encountering a paramagnetic deep level defect in a semiconductor like silicon. For simplicity, again suppose that the defect involved is a dangling bond. If the spin quantum number of the unpaired electron in the dangling bond and the conduction electron are the same, the capture event is forbidden by the Pauli exclusion principle. However, if the spin quantum numbers are different, the trapping event will be allowed, just as was the case in trap-to trap tunneling. The absence of a magnetic field can allow for a mixing of the two possible states and therefore a larger recombination current at zero magnetic field.

In both cases considered here, we have significantly simplified reality to the extent that the utility of the response may not be obvious. A key first modification to this oversimplified model is to include the effects of local magnetic fields. The effective magnetic field at the defect sites is not simply the externally applied field but a field which also includes contributions from the immediate surroundings of the defects. These contributions primarily include hyperfine interactions, that is local magnetic fields due to nearby magnetic nuclei, possibly as well as magnetic fields due to nearby unpaired electrons. These local fields will result in the NZFMR response having a breadth which approximately corresponds to the magnitude of the local magnetic fields surrounding the electronic defects under observation. In some technologically important cases, clearly identifiable features in the NZFMR response can be interpreted to identify atomic scale structure. Additional features can provide information about the kinetics of observed transport phenomena. Since many of the observed phenomena have been extensively explored through EPR and EDMR, they are generally well understood. Thus, by extracting hyperfine interactions and interactions due to the magnetic fields of nearby paramagnetic centers we can obtain atomic scale interactions about defects which affect the performance of devices. Note that the NZFMR response is exclusively sensitive to those defects which affect device performance because the NZFMR response is itself based on a measurement of device response.

A full understanding of the NZFMR phenomena requires a much more sophisticated analysis, based upon the stochastic quantum Liouville (SLE) equation. Aspects of this approach were originally used by Wagemans et al. [9] for analysis of transport in organic semiconductors. The approach has been significantly extended by Flatte and Harmon [10],[11]. Quite recently the approach has been applied to studies of performance and reliability physics defects in semiconductor devices by Frantz et al. [5],[6]. We refer the interested reader to the work of Frantz et al. for an understanding sufficiently detailed for a quantitative interpretation of the NZFMR spectra. Although substantial quantitative understanding of NZFMR response is now available, it is not yet complete. However, current understanding of the NZFMR response provides substantial physical insight into the connection between NZFMR spectra and the physical and chemical nature of multiple defects which play important roles in device performance and reliability physics.

III. The NZFMR Measuring Apparatus

We can conveniently divide relevant NZFMR measurements into two categories: I and II. Those which require a constant but adjustable voltage applied to the device under study and those which involve a time varying voltage waveform.

I. Four types of NZFMR measurements which require only application simple constant voltage:

a) NZFMR via gated diode recombination measurements on metal /oxide/ semiconductor (MOS) devices, often called DCIV measurements,

b) NZFMR via the bipolar amplification effect (BAE) on MOS field effect transistors (MOSFETs),

c) simple measurements of currents domination by electron hole pair recombination in the depletion region of pn junctions,

d) simple measurements of leakage currents in thin dielectric films dominated by trap to trap tunneling.

II. Two types of NZFMR measurements require application of a time varying wave form voltage:

a) charge pumping measurements in MOSFETs

b) a variation on deep level transient spectroscopy

A schematic diagram of the category I NZFMR spectrometers is illustrated in Figure 1.

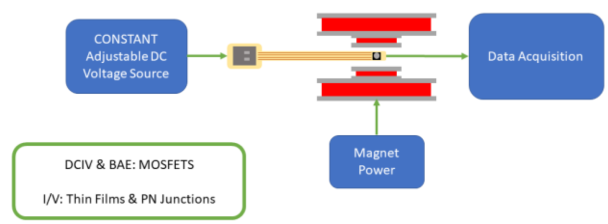

Figure 1. NZFMR apparatus with constant applied voltage to the device.

A schematic diagram of category II NZFMR spectrometers is illustrated in Figure 2.

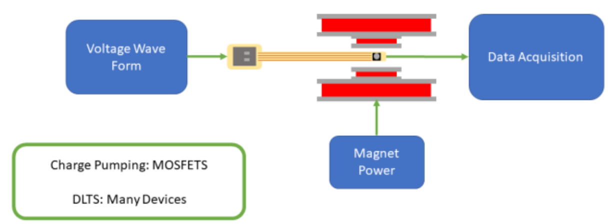

Figure 2. NZFMR apparatus with time varying voltage waveforms applied to the device.

In Figure 3, we illustrate: an electromagnet which we have utilized in NZFMR studies. Built almost entirely of aluminum, the large side plates effectively dissipate the modest amount of heat generated by the magnet currents. The electromagnet

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consists of nested Helmholtz coils, thus the field in the middle of the electromagnet is quite uniform. Additional uniformity may be obtained by placing the magnet in a zero Gauss chamber, but it has been our experience that the zero Gauss chamber is not necessary. The small Helmholtz coils required for the magnetic field modulation are mounted on the inside walls of the large electromagnet. The devices are mounted on a circuit board "tee." The devices are wire bonded to gold film leads on the circuit board and the tee is readily coupled to voltage sources and a current to voltage amplifier. The sample mounted on the tee is illustrated in Figure 4.

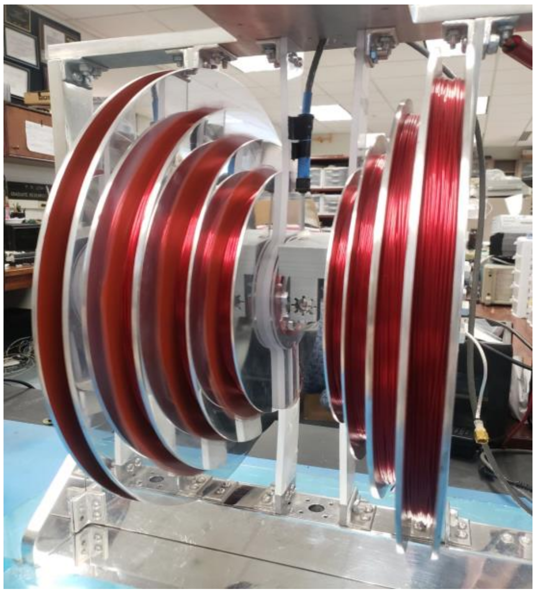

Figure 3. An electromagnet suitable for NZFMR measurements.

Figure 4. A device mounted to a tee. The tee widths are 4 millimeters with variable lengths.

The size of the NZFMR response is modest, even with the advantages of lock-in detection. To achieve high signal to noise (S/N) ratios, repetitive measurements allowing signal averaging are often required, especially if one wishes to detect small features in the NZFMR response which can be due to magnetic nuclei involved in the environment around the defects under study. Additional S/N enhancement is possible through the utilization of adaptive signal averaging techniques developed recently for electron spin related techniques by Cochrane et al. [12] and Manning et al. [13].

Inspecting Figures 1, 2, and 3, note that both systems incorporate standard or close to standard reliability physics laboratory apparatus with the addition of three things: an electromagnet which can provide modest (up to about 25 milliTesla) slowly time varying magnetic fields, a very small electromagnet consisting of a simple Helmholtz coil, for magnetic field modulation and a lock-in amplifier. The lock-in can be easily incorporated with software within the computer used in data acquisition. It would also be advisable to utilize a precision temperature compensated Hall Gaussmeter to guarantee precise and repeatable magnetic field control. The Helmholtz modulation coils and the larger electromagnet will, of course, require suitable programmable power. All of these components are inexpensive, readily available, and fairly inexpensive.

IV. NZFMR Measurement Results

We demonstrate the analytical capabilities of the NZFMR approach with several examples of relevance to semiconductor device reliability.

In Figure 5, we compare an NZFMR trace and an EDMR trace taken on the same high-field-stressed MOSFET [7]. No measurable EDMR or NZFMR response was visible prior to the stressing. The strong post-stress response in the EDMR measurement (made at about 0.34 Tesla and about 9.5GHz) has a strong central line and a pair of side peaks corresponding to hyperfine interactions with ^{29}Si nuclei. As earlier resonance work has demonstrated, these side peaks provide essentially incontrovertible evidence that the spectrum is due to two types of silicon/silicon dioxide interface silicon dangling bond defects. [7] Note the strong similarity in the EDMR and NZFMR side peak pattern, though in the NZFMR case the pattern is centered around zero magnetic field. Moxim et al. have argued in some detail why the NZFMR pattern is in fact due to the same silicon dangling bond centers. However, even a casual inspection of the data [7] suggests that this is the case.

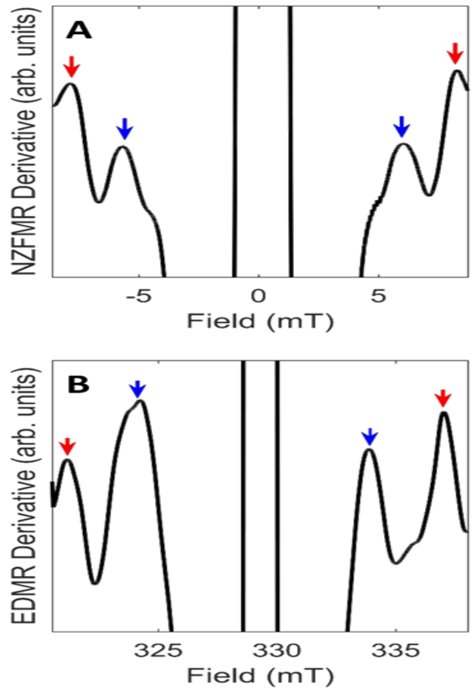

Figure 5. An NZFMR (above) and EDMR (below) trace taken on a gamma irradiated MOSFET. Note the prominent side peaks due to ^{29}Si hyperfine interactions coresponding to interface dangling bonds.. The traces are derivatives of the lock-in output and thus represent second derivatives of the absorption.

In Figure 6 we illustrate four NZFMR traces taken on identical-geometry metal oxide silicon structures in which we have, in one case eliminated both hydrogen and silicon magnetic nuclei, in another case removed just the silicon magnetic nuclei, in a third case removed just the magnetic hydrogen nuclei and in a fourth case have both magnetic hydrogen and silicon nuclei present. One can quite clearly observe the differences by casual inspection. Frantz et al. have provided a detailed analysis utilizing the SLE [5].

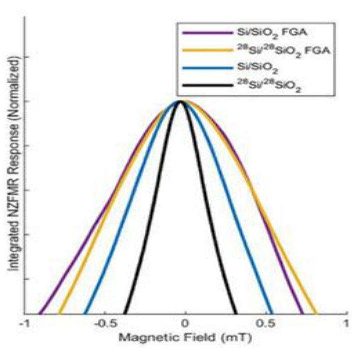

Figure 6. NZFMR results obtained via trap assisted tunneling in a leakage current in a silicon dioxide film on silicon [5]. The effects of magnetic nuclei during a forming gas anneal (FGA) and effects of silicon magnetic nuclei due to ^{29}Si are clearly evident within the traces. These traces were integrals of the spectrum taken using a lock-in amplifier.

In Figure 7, we illustrate an NZFMR derived spin dependent deep level transient spectroscopy race taken on a gamma irradiated MOSFET. As discussed by Myers et al. [14] this trace is due to silicon/ silicon dioxide interface traps. Myers notes that one may obtain, admittedly somewhat limited and modest precision density of states information from these measurements which can directly link the structure and chemistry of the defects to their electronic density of states.

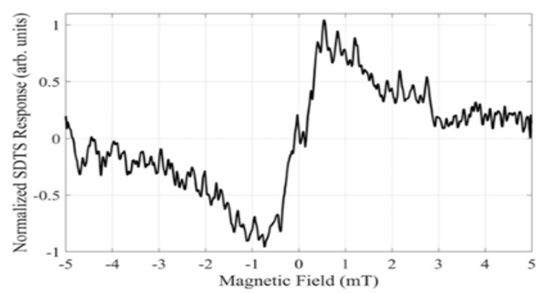

Figure 7. A trace of deep level transient spectroscopy NZFMR measurement taken on an irradiated MOSFET. The trace illustrated is approximately a derivative of the absorption taken directly from the lock-in output.

These few examples have been included simply to demonstrate in a limited way the potential power of this new NZFMR approach. We believe the potential utility of the approach is very great.

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