Wafer-Level Electrically Detected Magnetic Resonance: Magnetic Resonance in a Probing Station

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***Abstract*—We report on a novel semiconductor reliability technique that incorporates an electrically detected magnetic resonance (EDMR) spectrometer within a conventional semiconductor wafer probing station. EDMR is an ultrasensitive electron paramagnetic resonance technique with the capability to provide detailed physical and chemical information about reliability limiting defects in semiconductor devices. EDMR measurements have generally required a complex apparatus, not typically found in solid-state electronics laboratories. The union of a semiconductor probing station with EDMR allows powerful analytical measurements to be performed within individual devices at the wafer level. Our novel approach replaces the standard magnetic resonance microwave cavity or resonator with a small non-resonant near field microwave probe. Using this new approach we have demonstrated bipolar amplification effect and spin dependent charge pumping in various SiC based MOSFET structures. Although our studies have been limited to SiC based devices, the approach will be widely applicable to other types of MOSFETs, bipolar junction transistors, and various memory devices. The replacement of the resonance cavity with the very small non-resonant microwave probe greatly simplifies the EDMR detection scheme and allows for the incorporation of this powerful tool with a wafer probing station. We believe this scheme offers great promise for widespread utilization of EDMR in semiconductor reliability laboratories.**

***Index Terms*—EDMR, wafer level, semiconductor defects, magnetic resonance spectroscopy, reliability.**

I. INTRODUCTION

As SEMICONDUCTOR technology continues to scale and newer material systems are introduced, it is imperative to have reliability measurements that are capable of identifying performance limiting defects at the atomic scale. Currently, most reliability measurements are performed using wafer probing stations. Measurements made at these stations have proven widespread and high-volume applicability for purely electronic measurements of performance limiting imperfections, for example, semiconductor-insulator interface traps. However, these measurements yield essentially nothing with regard to the atomic-scale nature of the defects that ultimately govern reliability. The most powerful techniques for identifying atomic-scale defect structure in semiconductors, insulators, as well as semiconductor devices, are based upon electron paramagnetic resonance (EPR). EPR measurements within fully processed, technologically relevant devices, can be carried out with electrically detected magnetic resonance (EDMR). EDMR measurements were first demonstrated by Lepine in 1972 [6]. In EDMR measurements, one measures EPR of electrically active defects within a device via a spin-dependent change in device current or voltage. EDMR is at least ten million times more sensitive than conventional EPR [7]; it thus adequately addresses the sensitivity needs associated with advanced device structures, and can be applied to a wide variety of devices and device reliability problems [8]–[12]. The ubiquitous presence of wafer probing stations in solid-state electronics laboratories provides an opportunity for a novel EDMR apparatus based on such systems. In this paper, we demonstrate the viability of a wafer-level EDMR spectrometer utilizing a non-resonant near field microwave probe (Fig. 1). This approach is demonstrated via observation of Si-vacancy defects [8]–[10] which dominate the performance of SiC MOSFETs.

II. ELECTRICALLY DETECTED MAGNETIC RESONANCE

In conventional EPR measurements, a sample is placed in a microwave cavity with a high quality factor (Q), and subjected to a slowly varying magnetic field H, and an oscillating magnetic field of frequency υ. Conventional measurements are most often performed at X-band frequencies ($\upsilon \cong 9$ – 10 GHz), with swept magnetic fields in the range of $H \cong 3500$ Gauss. At resonance, the paramagnetic defect-spins flip by absorbing the energy from the oscillating magnetic field. This changes the Q of the cavity, which alters the power reflected

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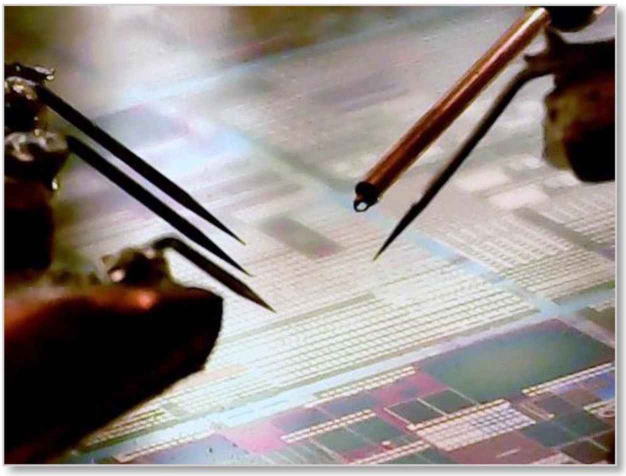

Fig. 1. Side view of the non-resonant near field microwave probe (top right) utilized in all EDMR measurements made in this paper. The four other probes are home-built high-frequency current probes used to measure device characteristics.

from the cavity. Essentially, the reflected power versus magnetic field constitutes the conventional EPR measurement. The sensitivity of such measurements is limited to $\sim$ 10 billion defects within the sample under study.

In the simplest case of an isolated electron in a strong magnetic field, the resonance condition is given by:

$$h\nu = g\mu_B H, \tag{1}$$

where h is Planck's constant, μ_B is the Bohr magneton, and again, in the simplest case of an isolated electron $g_e = 2.00232(\ldots)$. Many conventional resonance measurements are made at a strong magnetic field of about 3500 Gauss. In real material systems, the EPR response is most frequently dominated by two phenomena: spin-orbit coupling and electron-nuclear hyperfine interactions. In such a case, the spin Hamiltonian for the system is:

$$\mathcal{H} = \mu_B \vec{H} \cdot \overset{\leftrightarrow}{g} \cdot \vec{S} + \sum_i \overrightarrow{I_i} \cdot \left(A_i \vec{S}\right), \tag{2}$$

where $\vec{H}$ is the applied magnetic field vector, $\vec{S}$ is the electronic spin operator, $\overset{\leftrightarrow}{g}$ is the electron g dyadic, $\overrightarrow{I_i}$ is the nuclear spin operator for the ith nucleus, and A_i are the hyperfine parameters for those nuclei. The hyperfine parameters describe the interaction between the electron spin and the local-field due to nearby magnetic nuclei. Deviations from $g_e = 2.00232(\ldots)$ are due to effects of spin-orbit coupling.

As mentioned previously, the sensitivity limitations of conventional EPR are overcome with EDMR [6], an EPR technique in which resonance is observed through changes in device current or voltage.

The simplest EDMR measurements involve spin dependent recombination (SDR) within a p-n junction. A small forward-bias is applied to the junction, in which case the current is dominated by recombination within the depletion region. This recombination current is spin dependent. The spin dependent current is monitored as the magnetic field is swept over a range of fields, including the resonance condition, which in the simplest case would be described by equation (1). A detailed description of EDMR physics is beyond the scope of this report. The fundamental ideas were first expressed in the seminal paper of Kaplan, Solomon, and Mott (KSM) [7]. KSM were the first to realize that one must envision recombination events in terms of a pair of spins. The pair of spins could exist either as a triplet or a singlet. The magnetic resonance process, flipping the deep level defect spins, can alter the triplet to a singlet, which as they discuss, renders a previously forbidden event allowed, significantly altering the recombination rate. This leads to a change in current and constitutes the SDR/EDMR measurement.

Multiple EDMR schemes have been developed in recent years, several of which are relevant to MOSFETs. A few of these methods, including the bipolar amplification effect (BAE) and the spin dependent charge pumping (SDCP) technique, will be discussed in more detail within the Results and Discussion section [4], [5].

III. EXPERIMENTAL DETAILS

All MOSFETs analyzed with the wafer-level EDMR spectrometer were planar-type 4H-SiC n-MOSFETs, with 50 nm oxides, and varying gate sizes: 200 × 200 μm for SDR measurements, and 4 × 250 μm for the BAE and SDCP measurements. All EDMR measurements were made with the lab-built wafer-level EDMR spectrometer. This spectrometer was built by modifying a commercially available wafer probing station, and is illustrated in Fig. 2. The first addition was an annular neodymium permanent magnet (B_0) hung above the wafer chuck (Fig. 3 (a)), which provided the necessary magnetic field ($\sim$ 3300 Gauss) for X-band ($\sim$9–10 GHz) measurements. Second, a custom non-resonant microwave probe, shown in Fig. 3 (b) [1], was added to the wafer probing station. This probe consists of a very small coaxial probe with the center conductor extended out by 380 μm. A 10 μm diameter gold wire is used to connect the extended center conductor to the outer conductor. This creates the necessary current loop. The microwave probe introduces the oscillating (B_1) magnetic field necessary for EDMR. This probe, first developed by Campbell *et al.* [1] for use in scanned probe-like EPR measurements, was modified to handle more power and to generate larger oscillating magnetic field (B_1). An additional advantage of using this probe, insteadof the conventional microwave resonator, is to enable frequency swept measurements [2], [3]. The spectrometer is completed with the addition of four conventional electrical wafer probes. These probes are used to bias devices and measure the spin-dependent current.

IV. RESULTS AND DISCUSSION

The following section presents experimental results which demonstrate the capabilities of the wafer-level EDMR spectrometer. The wafer-level spectrometer is capable of all of the conventional biasing schemes typically used in conventional EDMR; however, these measurements are performed on a fully processed, unaltered wafer. The transistor is biased in a variety of schemes to allow for the measurement of spin-dependent

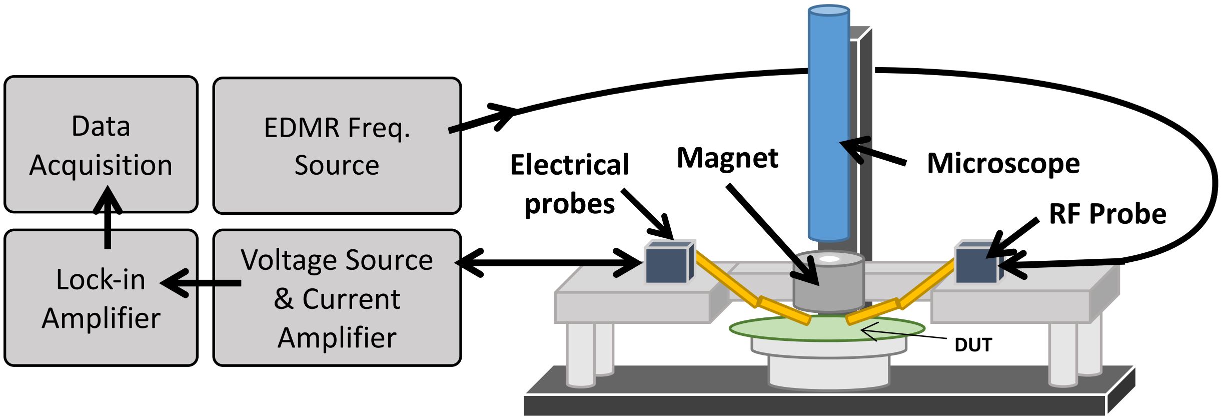

Fig. 2. Illustrates a schematic diagram of the vital components of the wafer-level EDMR spectrometer. This spectrometer eliminates the need for sample preparation and conveniently merges with a conventional wafer-probing station.

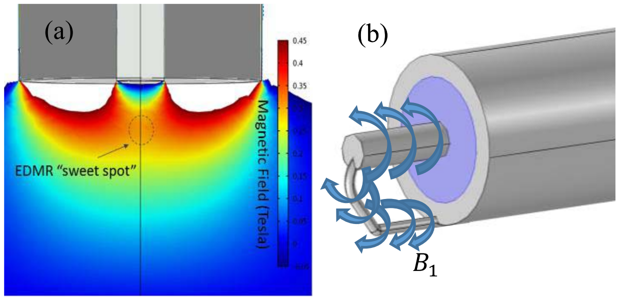

Fig. 3. (a) A finite element simulation of the neodymium permanent magnet. The illustration shows the EDMR "sweet spot" where the magnetic field is uniform over 300 µm × 300 µm. (b) illustrates the ∼ 9GHz oscillating magnetic field (B_1) necessary for X-band resonance. The field uniformity for the probe is ∼ 200 µm × 100 µm.

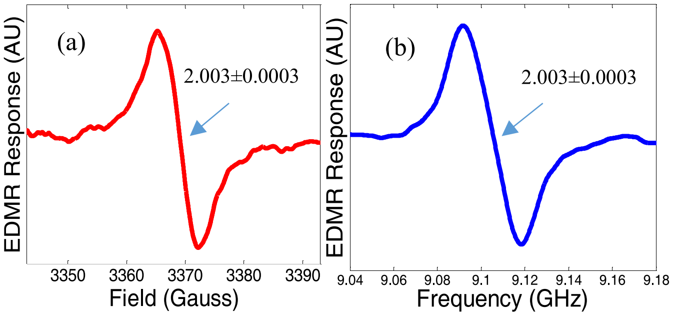

Fig. 4. (a) Conventional field swept EDMR of the 4H-SiC source-substrate. (b) FM frequency swept EDMR of the same junction. −2.5 V was applied to the source contact for both measurements.

current participating in the BAE, SDCP and SDR approaches. EDMR with each of these biasing schemes was performed via frequency modulated frequency sweeps.

A. Spin Dependent Recombination (SDR)

Figure 4(a) illustrates *conventional* field-swept magnetic field resonator-based EDMR of the SDR current in the source-body junction of the n-channel 4H-SiC MOSFET. The Si vacancy [8]–[10] participates quite strongly in this detection resulting in a large EDMR response (S/N ≈ 20/1) measured in a single 160 second long sweep. In this measurement the field modulation amplitude of 5 G at 1 kHz. Sample preparation for the conventional EDMR measurement involved SiC wafer dicing, silver-paint mounting, and wire-bonding to the device contact pads. In terms of ease of use, the wafer-level EDMR approach provides a huge advantage by eliminating sample preparation altogether. Figure 4(a) illustrates the conventional EDMR response of a silicon vacancy in a 4H-SiC MOSFET. The performance limitations due to this defect are well established [8]–[10]. We have chosen this well-characterized defect system for a demonstration of the utility of wafer-level EDMR.

Figure 4(b) illustrates the X-band frequency-swept FM detected EDMR response of the source-substrate junction recombination current of the same SiC MOSFET illustrated in Fig. 3 (a). We observe the same Si-vacancy defect center ($g = 2.003$). In this measurement, the FM depth was 16 MHz, and the FM rate was 10 kHz. The total acquisition time was the same (160 s) as in the conventional measurement (Fig. 4(a)). For this measurement, the input microwave power was 1 mW. In order to ensure that the device was well within the uniform region of the oscillating magnetic field, the probe was placed on the surface of the wafer, adjacent to the junction (the probe is not in electrical contact to the device pads).

A comparison of the conventional field-swept and wafer-level frequency-swept measurements can be made by realizing that 1 G is approximately equal to 2.8 MHz. Comparing the frequency swept measurement with the magnetic field swept measurement provides a higher signal to noise ratio for the frequency swept wafer probe measurement.

Further information about the defect can be obtained from analysis of the SDR/EDMR response as a function of the source-body bias. Figure 5 (a) and Fig. 5 (b) illustrate a comparison of the source-body current, and the SDR/EDMR response of the source-body junction as a function of bias.

These responses look very different, as they should. We can readily test the assumption that we are indeed observing recombination in the source-body junction by considering standard elementary text book expressions for recombination currents within the depletion region of a p-n junction [14]. Consider recombination in a forward biased p-n junction.

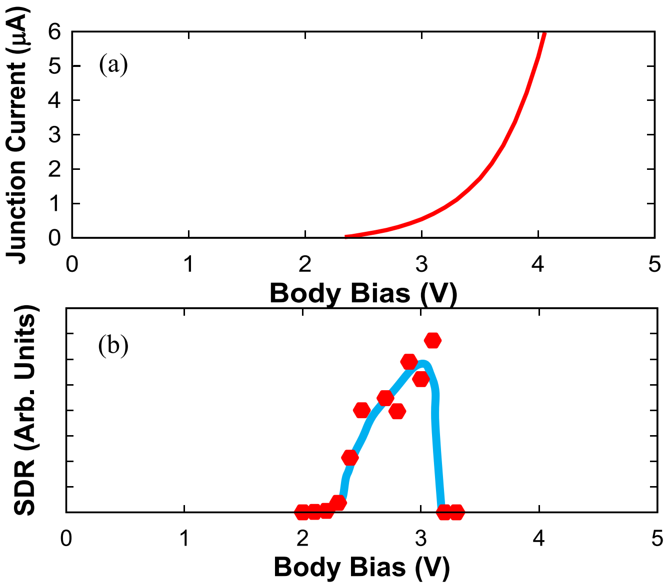

Fig. 5. (a) The current versus voltage characteristics of the source-body junction of the planar-type 4H-SiC n-MOSFET. (b) The SDR response of the source-body junction of the same 4H-SiC MOSFET as a function of body bias.

The equation for recombination reveals that SDR should be proportional to the recombination current. The recombination current peaks slightly below the build-in voltage of the p-n junction. The built-in voltage (V_{bi}) can be calculated utilizing the doping concentrations $N_D = 5 \times 10^{18}/cm^3, N_A = 6 \times 10^{16}/cm^3$, and $n_i = 5 \times 10^{-9}/cm^3$. Given these parameters, $V_{bi} \cong 3.1V$. Figure 5 (b) illustrates the SDR amplitude peaking just before the built-in voltage. This response is fairly consistent with what would be expected in a typical planar p-n junction response.

B. Bipolar Amplification Effect (BAE) and Spin Dependent Charge Pumping (SDCP) Techniques

The SDR current demonstrations above provide information about deep level defects in the depletion region of source to body junction. Refinements of this measurement can allow a more precise focus specifically on the channel region and interface [4], [5], [12]. These new approaches are the BAE and SDCP measurements. In the BAE biasing scheme, the transistor gate is biased in the sub-threshold ($V_G < 10V$) regime such that the source-drain current is subject to many recombination events within the entire channel region [4]. These recombination events are spin dependent and their rate is altered at the resonance condition. In the BAE approach, the field effect transistor is biased such that it behaves like a very poor bipolar junction transistor with the channel region substituting for the base region [4]. EDMR measurements in this biasing scheme provide information about the interface traps which influence device current. Fig. 6 illustrates the frequency-swept FM-modulated BAE measurement on the narrow (250 μm × 4 μm) SiC device.

In this measurement, the gate was biased at $V_G = 4V$, with $-2.9V$ on the source electrode, while the drain and substrate electrodes are grounded. As in the previous cases, this signal was acquired in 160 s with S/N ratio of ≈100/1. Again, a wafer-level EDMR measurement, in this case BAE, provides rapid acquisition of high signal to noise measurement.

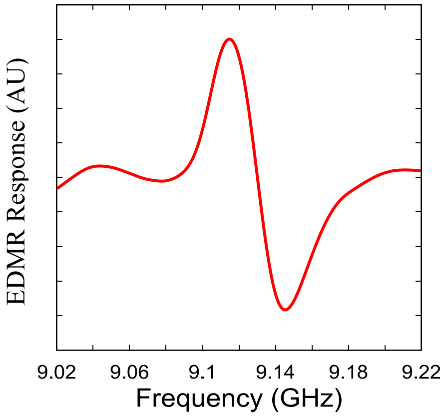

Fig. 6. EDMR of the same 4H-SiC MOSFET utilizing the BAE biasing scheme. $V_G = 4V$ and $-2.9V$ applied to the source of the MOSFET.

The previous spin-dependent current measurements, which were shown in Fig. 4 through Fig. 6, involved SDR with defects levels around the middle of the bandgap. In studies of MOSFETs, one is interested in defects levels throughout the entire semiconductor bandgap. As Anders *et al.* [12] have recently pointed out, SDCP can provide such a measurement. SDCP is based upon conventional charge pumping. A trapezoidal waveform is applied to the gate electrode. This trapezoidal waveform cycles the device between accumulation and inversion and alternately fills the SiC/SiO$_2$ interface states with holes and electrons. This scheme can explore most of the interface semiconductor bandgap. In limited proof of concept measurements, we have observed SDCP in these transistors with reasonably consistent results.

In these measurements, the gate voltage maximum and minimum were respectively +16 V and −16 V. The frequency utilized was 200 kHz with rise/fall times of 1 μs. Detection utilized FM modulation at 10 kHz with a modulation amplitude of 8 MHz.

V. CONCLUSION

As semiconductor technology continues to scale and new materials systems are utilized, reliability measurements need to keep pace with the advancing technology. We have demonstrated the feasibility of wafer-level EDMR. The EDMR spectrometer is merged with a conventional wafer probing station. This spectrometer has demonstrated sensitivity at least as good as, and probably somewhat better than, a conventional EDMR spectrometer. The wafer-level EDMR spectrometer is capable of performing previously utilized EDMR biasing schemes for MOSFETs, and eliminates the need for sample preparation.

This union of an EDMR spectrometer with a semiconductor wafer probing station could help make EDMR a widely utilized technique for semiconductor reliability measurements.

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