Wafer Level EDMR: Magnetic Resonance in a Probing Station

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Abstract— **We report on a novel semiconductor reliability technique that merges electrically detected magnetic resonance (EDMR) with a conventional semiconductor wafer probing station. This union with a semiconductor probing station allows EDMR measurements to be performed at the wafer level. Our measurements forgo a microwave cavity or resonator for a very small non-resonant near field microwave probe [1]. Bipolar amplification effect (BAE) [4] and spin dependent charge pumping (SDCP) [5] were demonstrated on various SiC MOSFET structures. These measurements were made via frequency-swept EDMR. The elimination of the resonance cavity, and incorporation with a wafer probing station, greatly simplifies the EDMR detection scheme and offers promise for widespread EDMR adoption in semiconductor reliability laboratories.**

*Keywords— **EDMR; wafer level; defects; magnetic resonance; 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. The electrical measurements made at these stations have proven widespread and high-volume applicability for counting charges in device measurements. However, these measurements yield limited information about the atomic-scale nature of the defects that capture and emit charges and ultimately govern reliability. The most sensitive technique for identifying atomic-scale defects in semiconductor devices is electrically detected magnetic resonance (EDMR). This technique, first proposed as spin dependent recombination (SDR) by Lepine in 1972 [6], is a derivative of electron paramagnetic resonance (EPR) in which the measurement is performed on fully processed device structures. EDMR is at least ten million times more sensitive than conventional EPR [7], and thus adequately addresses the sensitivity needs associated with advanced device structures. EDMR is a powerful tool for investigating performance limiting defects in many different material systems [7]-[11]. Unfortunately, EDMR measurements require significant sample preparation and bulky spectrometers. Despite the rich information provided by EDMR, the experimental barriers relegate it as a niche technique only suitable for individual device measurements. Clearly there is a need for an EDMR spectrometer that eliminates sample preparation and can be incorporated into a conventional wafer probing station. 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

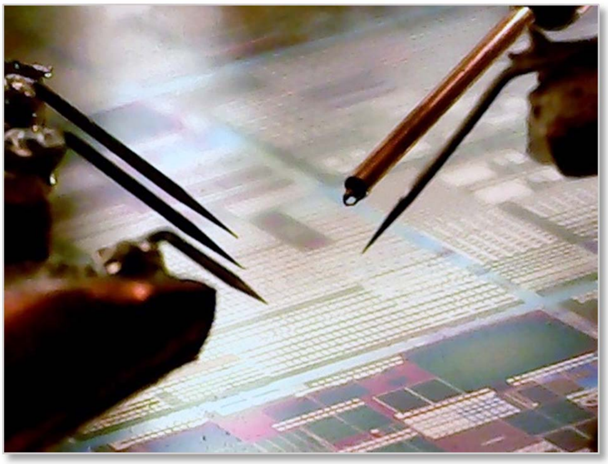

Fig. 1. Side view of the non-resonant near field microwave probe (top right) utilized in all EDMR measurements made in this paper. The four other probes are home-built high-frequency current probes used to measure device characteristics.

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observation of Si-vacancy defects [7]-[8] which dominate the performance and reliability of SiC MOSFETs.

II. EXPERIMENTAL DETAILS

All MOSFETs analyzed with the wafer-level spectrometer were 4H-SiC n-MOSFETs with varying gate sizes: 200 × 200 µm for SDR and 4 × 250 µm for the bipolar amplification effect (BAE) and spin dependent charge pumping (SDCP) measurements.

All EDMR measurements were made with the lab-built wafer level spectrometer. This spectrometer was built by modifying a commercially available wafer probing station. The first addition was an annular neodymium permanent magnet (B_0) hung above the wafer chuck (Fig. 2(a)), which provided the necessary magnetic field (~3300 Gauss) for X-band (~9 GHz) measurements. Second, a custom non-resonant microwave probe, shown in Figure 2(b) [1], was added to the wafer probing station. This probe introduced the oscillating (B_1) magnetic field necessary for EDMR. The microwave probe, first developed by Campbell et al. for use in scanned probe-like EPR measurements, was modified to handle more power and to generate larger B_1. The purpose of using this probe instead of the conventional microwave resonator, is to enable frequency swept measurements. Sweeping the frequency has many experimental advantages [2]-[3], and has the promise of improved sensitivity at increased microwave powers. 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.

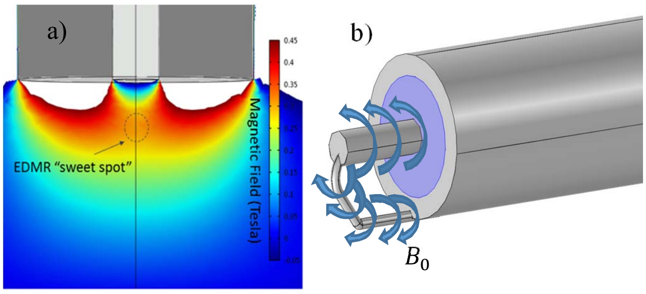

Fig. 2.(a) A finite element simulation of the neodymium permanent magnet. The illustration shows the EDMR "sweet spot" where the magnetic field is uniform over 200 µm. (b) illustrates the ~9GHz oscillating magnetic field (B_0) necessary for X-band resonance.

III. RESULTS AND DISCUSSION

The following section presents experimental traces 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 current participating in the BAE, SDCP and SDR approaches. EDMR with each of these biasing schemes was performed via frequency modulated frequency sweep.

A. Spin Dependent Recombination (SDR)

Figure 3(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 [7]-[8] participates quite strongly in this mode of detection resulting in a large EDMR response (S/N ≈ 20/1). This single sweep measurement was acquired in 160 seconds with a field modulation amplitude of 5 G at 1 kHz. Sample preparation for this measurement involved device identification, SiC wafer dicing, silver-paint mounting, and wire-bonding to the device contact pads. This preparation is required for every single device investigation. In terms of experimental ease of use, the wafer-level EDMR approach presents huge experimental benefits by eliminating sample preparation. While the reliability and performance limiting nature of the Si vacancy defect shown in Figure 3(a) certainly merits further study, we have instead chosen to use this defect system as a practical demonstration of the utility of the wafer-level EDMR measurement approach.

Figure 3(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 Figure 3 (a). We again observe the same Si-vacancy defect center (g = 2.003). In this measurement, the frequency sweep rate was 100 GHz/s, 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. 3(a)). For this measurement, the input microwave power was 1 mW and the microwave probe was touching the surface of the wafer.

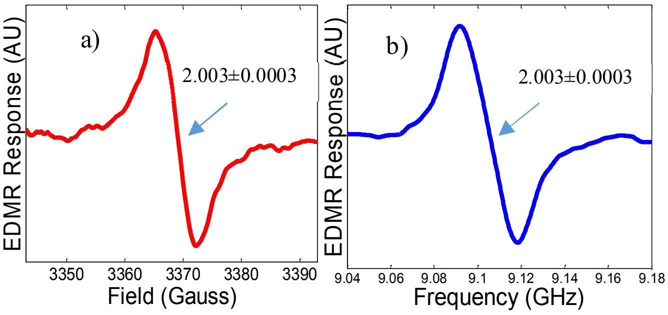

Fig. 3. (a) Conventional field swept EDMR of the 4H-SiC source-substrate. (b) FM frequency swept EDMR of the same junction. -2.5 V was applied to the source contact for both measurements.

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 shows similar, if not slightly improved, signal to noise ratio for comparable scan settings.

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 channel junctions. Variations on this measurement's biasing scheme can shift the focus from the junction to the channel region [4] and even the interface [5], [11]. These new approaches, are BAE and SDCP respectively. In the BAE biasing scheme, the transistor is biased in the sub-threshold regime such that the source-drain transport current is subject to many defect scattering events [4]. Similar to recombination in junctions, these scattering events can be rendered spin dependent at the resonance condition. Thus, the field effect transistor is biased such that it behaves like a bipolar transistor with the channel region substituting for the base region [4]. EDMR measurements in this biasing scheme provide information about the channel defects which influence transport current. As the Si-vacancy defect in SiC devices is known to dominate nearly all defect mediated currents in these devices [7]-[8], it serves as a good test for this wafer-level non-resonant EDMR measurement. Figure 4 illustrates the frequency-swept FM-modulated BAE measurement on the narrow (250 µm × 4µm) SiC device.

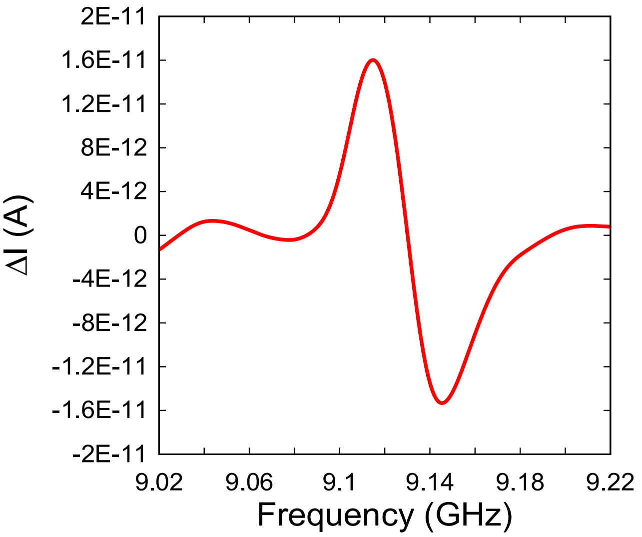

Fig. 4. EDMR of the same 4H-SiC MOSFET utilizing the BAE biasing scheme. $V_G - V_{th} = 1$ V and -2.9 V applied to the source of the MOSFET.

In this measurement, the gate was biased at $V_G - V_{th} = 1$ V, with $-2.9\ V$ on the source electrode, while the drain and substrate electrodes where grounded. This signal was acquired in 320 s with S/N ratio of ≈100. BAE is an extremely useful biasing technique that has greatly increased the signal to noise of our response, identifying the Si-vacancy defect that severely limited mobility in early SiC devices.

The previous spin-dependent current measurements, which were shown in Figures 3 and 4, were acquired in a steady state biasing scheme. The biases were chosen in order to have an approximately equal numbers of electrons and holes present for recombination. In order to increase the recombination events per unit time, we can utilize a different biasing scheme, SDCP. This active biasing scheme utilizes a square wave (50% duty cycle) that is applied to the gate electrode. The square wave cycles the device between accumulation and inversion and alternately fills the SiC/SiO$_2$ interface states with holes and electrons. This active biasing scheme can probe a larger energy window of defect sites relative to BAE, increasing the likelihood of identifying performance related defects within the MOSFET. Figure 5 shows SDCP detection of the Si-vacancy defect in the narrow (250 µm × 4 µm) SiC device.

For this measurement, the gate voltage waveform oscillated between +16 V and -16 V at a frequency of 200 kHz with rise/fall times of 1 µs. Detection utilized FM modulation at 10 kHz with a modulation amplitude of 8 MHz. This signal was acquired in 320 s with S/N ratio of ~10. SDCP is an extremely useful biasing scheme for probing nearly the entire energy gap of the semiconductor, while looking at defects located primarily at the interface. This technique is also impactful due to the ability to compare the size of the SDCP response to the approximate defect counts at the interface via conventional charge pumping.

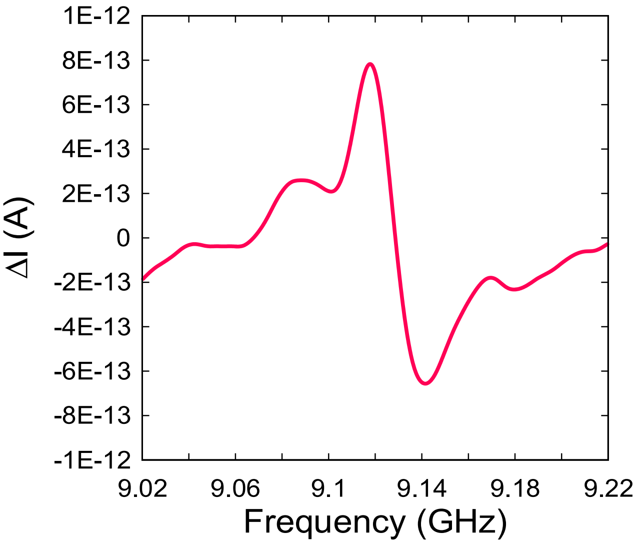

Fig. 5. SDCP of the same 4H-SiC MOSFET with ±16V square wave applied to the gate with a rise/fall time of 1µs.

IV. 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 the wafer level EDMR spectrometer that is merged with a conventional wafer probing station. The spectrometer has demonstrated comparable, if not enhanced sensitivity in relation to conventional EDMR spectrometers. The wafer level spectrometer is capable of performing all of the conventional EDMR biasing schemes for MOSFETs. This spectrometer eliminates the need for sample preparation, performing all measurements on fully processed wafers.

The union of an EDMR spectrometer with a semiconductor wafer probing station has proven feasible and promising. We believe this technique could help make EDMR a prominent technique for semiconductor reliability measurements.

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