2.1 RC1: 'Comment on mr-2024-11', Anonymous Referee #1, 10 Aug 2024

We would like to thank the reviewer for their assessment of our manuscript. We have replied to the different comments separately below. Note that we indicate the line numbers as in the new version of the manuscript.

1. ***The EPR chip is small, but the entire experimental setup includes many components (synthesizer, current amplifier, etc.). It would be helpful to show all these devices in a schematic drawing and highlight the role of the EPR chip and what it saves over a conventional setup. Specifically, it would be useful to understand if the EPR chip in this context can simply be replaced by a small broadband antenna.***

As mentioned in the manuscript, the EPR chip with external compact magnet replaces the microwave source, the microwave resonator (and its intrinsic restriction to use a fixed microwave frequency) and the sweepable electromagnet. All other components are conventional scientific instruments, that are relatively cheap and can be easily found in many laboratories. Note that it can in principle even be much cheaper than the demonstrated instruments, as many of those we used in this work are multi-purpose lab instruments with different functionalities that are not fully required for this application.

The setup is schematically illustrated in a new figure in the appendix I, Figure I1.

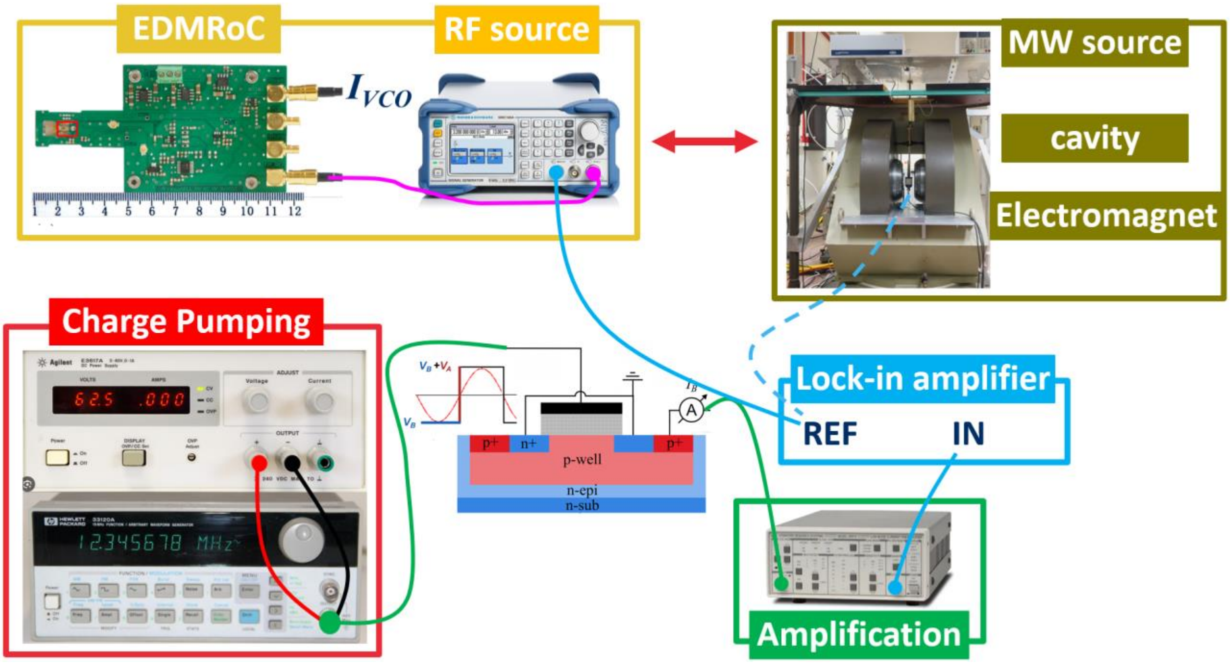

Figure I1: Schematic setup of the experiment. For the charge pumping we employ a HP33120A function generator, giving a sinusoidal excitation with an amplitude V_A of 10 V. The base voltage VB can be varied using a DC power supply. This sinusoidal excitation is provided to the gate of the device, with the source and drain grounded and the charge pumping current is measured at the body of the device, amplified by the TIA (SR570) to a detectable input voltage for the lock-in amplifier. For cavity-based EDMR, a microwave source is combined with a microwave cavity, in between the poles of a sweepable electromagnet, while for EDMRoC the MWs of the chips are locked on an RF source (SMC100B), off which the 32nd harmonic is used to generate the MWs. The required frequency of ~450 MHz could readily be obtained from a more basic RF source. The I_{VCO} is of the EDMRoC is provided by a standard DC current source. For frequency modulation, the modulation signal is provided to the lock-in amplifier as a reference, while for magnetic-field modulation, both in cavity-

based EDMR and EDMRoC, the reference to the lock-in amplifier comes from the control unit of the EPR spectrometer. Note that for all experiments reported here, we made sure that the MOSFET device, charge pumping parameters as well as amplifier and lock-in amplifier settings were all kept identical, so that EDMRoC and cavity-based EDMR can be ideally compared. For the lock-in amplifier, the SPU unit of our Bruker EPR spectrometer is used, but it can be replaced by any lock-in amplifier for EDMRoC.

Replacing the MW ASIC on the EDMRoC board by an antenna is not possible, since the VCOs are an integrated part of the MW generation circuitry. One could, in principle, replace the EPR chip by a broadband antenna, but at a significant cost in complexity, size of the setup and overall costs. For example, if one would like to achieve comparable excitation volume with comparable B_1 strength at the same frequency, one would need a 14 GHz signal generator combined with a power amplifier with significant power output. The advantage of the EPR chip is that it only needs an approximately 450 MHz frequency reference with frequency modulation capability, here provided by the SMC100B. This instrument is however overkill and could in a later design be replaced with a single PCB. Moreover, as we mention in the discussion section of our manuscript, the MW ASIC is scalable (not limited to the 2 rows of 6 coils) and can thus be adapted to match smaller or larger planar samples and thus provide a larger excitation volume.

Importantly, as demonstrated previously, one can combine the EPR chip with a PCB for delivering the reference frequency with modulation capability, and another PCB with the necessary power supplies and lock-in amplifier for signal detection, which could fit the whole spectrometer into 10x10x10 cm^3 operated by a battery [doi: 10.1109/ISSCC.2016.7418114]. The prize of such a spectrometer would depend on the number of spectrometers that are produced but amounts to a few hundred euros per chip depending on technology, chip size and demand (in the case of a demand of less than 100 units). For medium-scale production, the cost per chip will decrease to less than hundred euros, making it a low-cost solution comparable to a typical cavity-based EDMR spectrometer that can easily amount up to 500.000 euro.

We added a remark regarding this on lines 395-398 in the revised manuscript:

Finally, it is important to note, that the reference frequency of the VCO (here provided by the SMC100B), the DC power supply and the current source (I_{VCO}) to operate the EDMR chip can in principle be replaced by small dedicated PCBs that can even operate with a battery, so that the entire setup can fit in a very small spectrometer, as previously demonstrated in (Handwerker et al., 2016), further reducing the costs of the system to just a few hundred euros.

2. ***It would be beneficial to add a figure that summarizes and explains the CP mechanism in the MOSFET device.***

The essentials of CP are described in the introduction of our manuscript and in section 2.1.4 “Charge pumping and EDMR Detection” of the manuscript. We have also presented a schematic drawing of CP in Figure 2(f) and the necessary equipment is added in the new Figure I1. CP is a commonly used technique for characterizing defects in MOSFET devices, and references to the literature are provided (e.g. Groeseneken 1984 and Okamoto 2008 and Lettens 2023) which explain the technique in detail. Since it is not essential to the current manuscript, CP being used to generate a direct current which is known to be spin-dependent, we decided to not complicate the manuscript with a more detailed explanation.

3. ***Regarding the text "MOSFET device," does it resemble a real device, or is this just a test sample? What does a real sample look like, and what are the prospects of measuring a real sample?***

As explained in section 2.1.2 in our manuscript (“The MOSFET device”) as well as in section 2.13 (‘Mounting of the MOSFET device”), it is a lateral n-type MOSFET test device. Commercial SiC power MOSFETs are vertical transistors, with the drain contact at the bottom of the die (SiC substrate). These devices always have shorted source/body contacts, which makes the measurement and interpretation of charge pumping more challenging. Typically, for advanced characterization, simple test-structures are used, in our case a lateral n-type MOSFET. These devices are much simpler and also have a separate source/body contact which allows to measure the hole recombination current which is required in charge pumping. The source and *p*-body, gate oxide and gate poly and metal are the same as for the vertical SiC power MOSFETs. Hence the results extracted on a lateral test-structure about the SiC/SiO_2 interface are directly transferable to a vertical device.

Recently, CP EDMR has been reported on such commercial SiC power MOSFETs [Lew et al., J. Appl. Phys. 134, 055703 (2023); doi: 10.1063/5.0167650], hence there is in principle no limitation to apply CP-EDMRoC also to commercial power MOSFETs, and in this case the EDMR chip can be adapted to match the size and excitation volume of those MOSFETs.

We have added the following sentences in section 2.1.2 of our revised manuscript (lines 124-128)

"Note that commercial SiC power MOSFETs are vertical transistors, with the drain contact at the bottom of the SiC substrate. These devices always have shorted source/body contacts, which makes measurements and interpretation of charge pumping more challenging. Therefore, lateral test structures are devised with identical materials and processing of the source, drain and body, the gate and gate oxide, as in the vertical SiC MOSFETs, so results are directly transferable."

We have also added the following sentence in section 3 of our manuscript and added a reference to this paper (lines 351-352 in revised manuscript):

"While in this work we focused on lateral test MOSFETs, a recent report demonstrated the power of CP-EDMR also on commercial SiC MOSFETs, showing the versatility of CP-EDMR.(Lew et al., 2023)"

4. ***Figure 2c - Where are the n, p, and gate parts in the structure shown in 2c?***

Figure 2(c) is a top view picture of the MOSFET device showing contrast based on the surface materials, in particular metallization and a-SiO2 isolator, hence the n, p and gate parts are difficult to indicate. To clarify, we have added the Source (S), Drain (D), Body (B) and Gate (G) contact pads in Figure 2(c). This can then be directly related to the schematic cross-section of the device presented in figure 2(f) where the different contacts are given. The body is the p+ contact where I_B is measured, while source and drain are the n+ contacts. The gate is in black.

We have thus adapted Figure 2 accordingly and added this information to the caption of Figure 2.

5. ***Figure 2e - Please add a scale bar to this figure to appreciate the distances.***

We have added a scale bar to this panel.

6. ***Line 157 - An illustrative figure for the spin resonance effect in the measured material would be helpful to include.***

In the (quite extensive work) on this topic in literature only fragmentary explanation of the spin resonance effect for EDMR in SiC MOSFETs has been previously provided, and this is even more the case for CP-EDMR. We have cited the most relevant literature in the introduction of our manuscript (pages 1-2). This manuscript reports on an alternative experimental approach for these measurements, independent on which spin-dependent current is probed. We estimate that the more detailed description of the spin resonance effect is beyond the scope of this report.

7. ***Line 205 - It would be useful to see the B1 field superimposed on the measured sample in Figure 2c.***

We estimated that adding the calculated B_1 field superimposed on the sample in Figure 2c would make the figure overcrowded. Therefore, we had previously added an overlay of Figure 2c on top of the microwave chip in appendix D (Figure D1). Moreover, in appendix G1, the B_1 field is presented in figure G1, hence we believe this was already provided, be it in two complementary figures in the appendices of the manuscript. We have therefore added the following sentence on line 232 of the revised manuscript:

Note the overlap of our MOSFET sample with the microwave ASIC, as presented in Appendix D, Figure D1.

8. ***Line 257 - This section is repetitive of the previous subsection. Consider rearranging it to avoid redundancy.***

While in the previous section 2.2.1 we explain how to rescale the different MW powers in the two setups, in section 2.2.2 we make the actual comparison between both systems. We therefore only found one sentence overlapping, which we have deleted:

~~*"These SNR comparisons are taken at matching effective power levels, as derived earlier based on the signal saturation behavior in both configurations (see also Appendix A and B)."*~~

To delete this sentence, we added on line 276: "*..... at matching effective power levels."*

9. ***What is the (calculated?) static magnetic field profile/homogeneity for the permanent magnet?***

We do not have a calculation of this field profile. In the current simple design, the positioning of the sample is thus critical (within 0.5mm accuracy) to obtain optimal line widths. Moving the sample in any direction of this optimized position results in broadening of the line shape. Since permanent magnets with better field inhomogeneity are for sale at reasonable prices, it would only require a minor investment to improve this field homogeneity.

We did already mention this briefly in the manuscript on lines 332-334 and mentioned that this is the current limitation of the simple design, but have now further added the following sentences to stress this:

Note that the small line broadening observed for the permanent magnet assembly most likely originates from a ~~**slightly more**~~ **less** ~~**in**~~homogeneous B_0 *field in this very simple design.* ***Indeed, the exact sample positioning needs to be accurate (within 0.5 mm) to obtain this specific line width and position of the EDMR spectrum.*** *While this demonstrator evidently calls for further smart design of the magnet/sample set-up (e.g., with better field homogeneity and/or easier access to the sample area) and of other components of the spectrometer, it gives a taste of the possibilities opening up for ultra-compact, low-budget and dedicated EPRoC and EDMRoC spectrometers.*

10. ***Line 360 - What about the use of methods like those in 10.1016/j.jmr.2015.02.010?***

In the latter very interesting paper (Hubresch et al., JMR2015) the focus is on applications of pulsed magnetic resonance using sophisticated generation techniques for the microwaves, including arbitrary wave generation (AWG) combined with up- (and down-) conversion which is justified to reach the aimed spectroscopic resolving power. It brings requirements on maximum size of the sample for sufficient B_1-field homogeneity as well. One also has to note that the excitation volume in this approach is much smaller than in our case, and due to the small diameter of the excitation short-circuit, one needs to deposit the excitation electrodes directly onto the sample of interest, as the B_1 decays with distance even more drastically than in our case.

Our approach is quite different and aims at a robust, low-cost spectrometer for sensitive detection of continuous-wave EDMR in operational MOSFET devices. We have demonstrated that the use of the MW generation based on VCOs efficiently serves this purpose. At this point, there is no straightforward path to applications of this platform for pulsed EDMR as in the proposed manuscript. Importantly, as mentioned in our answer to this referee's first remark, the EPR chip can theoretically be operated by a portable battery and reach B_1 strengths comparable to conventional setups.