National Aeronautics and Space Administration

FY23 Innovative Spontaneous Concepts Research and Technology Development (ISC)

Characterization of Silicon Carbide JFET for use as Magnetic Field Sensor in Silicon Carbide Magnetometer

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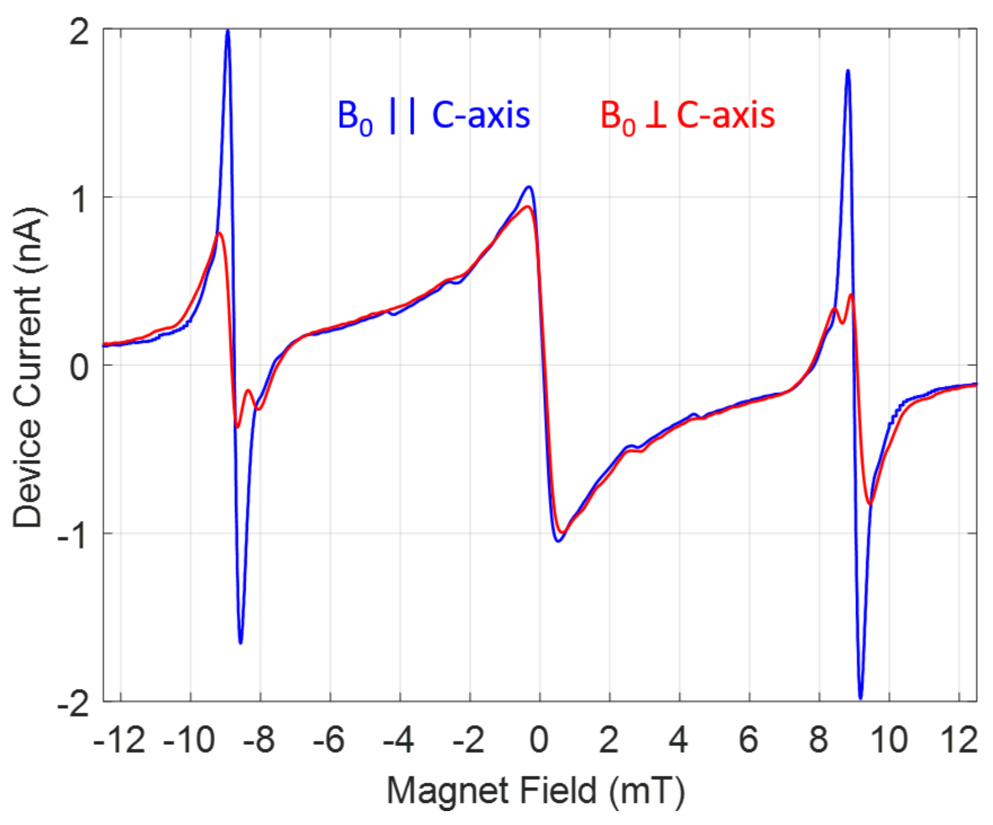
Objectives: We will characterize Silicon Carbide (SiC) Junction Field Effect Transistors (JFET) that were generously provided by Infineon Corporation who specializes in the development of SiC devices for power electronics. We will assess sensitivity metric which will ultimately determine whether or not these sensors are fit for scientific investigation of planetary bodies. For success, we are aiming for single-digit nT sensitivity which has actually already been demonstrated in other SiC devices and reported at the most recent International Conference on SiC and Related Materials (ICSCMR) conference.

Background: The SiC Magnetometer has the potential to revolutionize the way magnetometry is performed in space due to its unrivaled simplicity and improved SW&P once it is able to demonstrate sensitivity comparable to state-of-the-art technologies such as fluxgate and optically pumped atomic gas magnetometers (Cochrane et al. 2016). The instrument also has the advantage to simultaneously acquire both the vector field and absolute scalar field by leveraging spin properties of quantum centers intrinsic to the SiC semiconductor, thus facilitating self-calibration once in space without the need for complex spacecraft rolls or calibration coils. The focus of this spontaneous R&TD would be to characterize an already-fabricated JFET that has previously shown to a produce really large electrically detected magnetic resonance (EDMR) response, making the device ideal for use as the magnetic field sensing vessel in the SiCMag instrument. If successful, SiCMag could facilitate magnetic investigation of multiple scientific phenomenon on a variety of platforms, ranging from large scale spacecraft to smaller platforms including landers, rovers, and cubesats. In addition, the size and simplicity of the instrument allows for dozens of sensors to be accommodated on a spacecraft, thus providing measurement redundancy and very high order spacecraft magnetic field removal capabilities without the need of a boom.

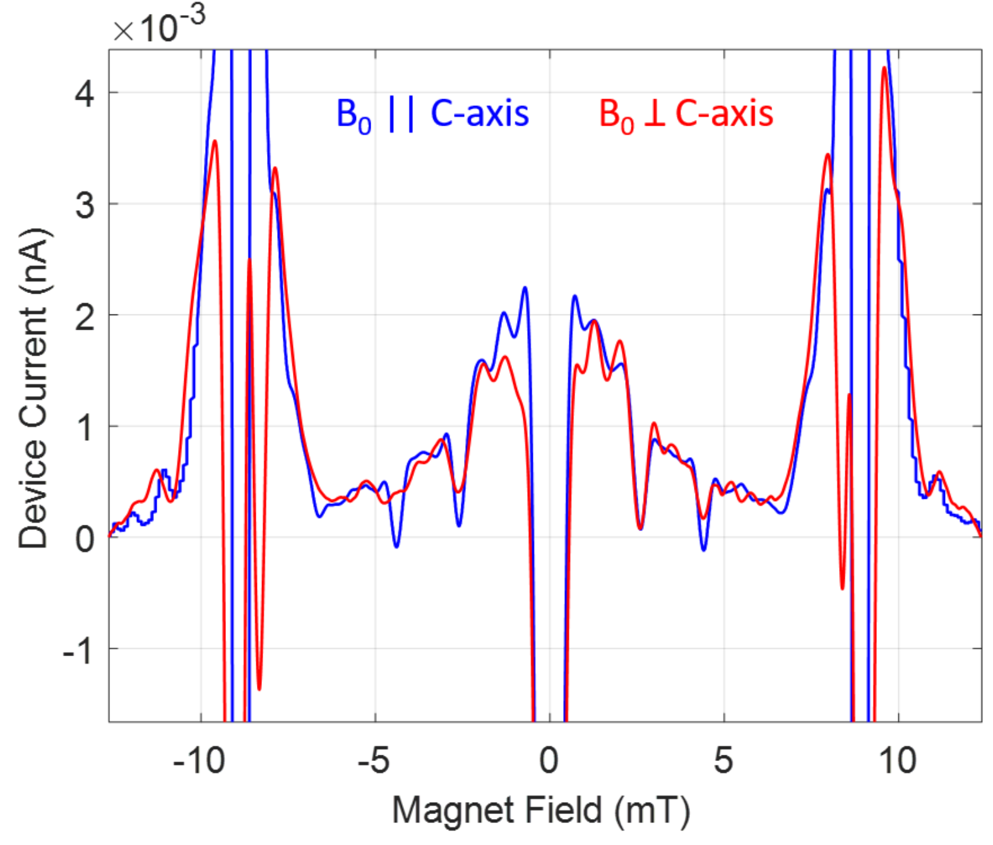
Approach: We combine the deep expertise and resources from both division 32 and 38 of JPL. We used the EDMR spectrometer developed under a previous PICASSO grant, located in the solid-state magnetometry lab (300-118), to characterize the quantum centers (atomic-scale defects) within the JFET magnetometer sensors and assessed their sensitivity. We also used the magnetically shielded chamber (i.e 'the mu-house'), recently upgraded by the Europa Clipper Magnetometer team for the ECM II&T campaign, to verify detection limit capability of the sensors being tested.

Results: In order to assess the sensitivity of the SiC JFET under study, we use the metric reported by Cochrane et al. 2016. We perform the EDMR measurement at multiple forward biases, then integrate the response to assess the change in current of the MR response. From the EDMR measurements obtained, we were able to extract a sensitivity of roughly 100 nT/sqrt(Hz). We then integrated the sensor into the benchtop SiCMag prototype, and tested it as a magnetic sensor using a calibrated stimulus field with axis-alternating square waves of amplitude +/- 1 µT to ensure we could detect magnetic signatures at this limit. Although an unoptimized setup was used to acquire this initial dataset, the acquired data still demonstrates the near-zero magnetic field sensing potential of this technology, making it a candidate for remote magnetic field in space. We also were able to determine the minimum magnetic field the sensor could operate in scalar EDMR mode without the need for a biasing coil to supply a larger field. Due to limitations in our hardware, the minimum RF field we could generate was at 2MHz, which produced a strong resonance response at 714 µT. A follow up study will be performed to determine the ultimate operable scalar mode field limit, once hardware is optimized. With the use of isotopically pure SiC device, one that is already being developed in a parallel effort, we anticipate that the potential scalar operability in the single- to double- digit micro-Tesla range, making the technology consistent with off-the-shelf proton precession and Overhauser magnetometers.

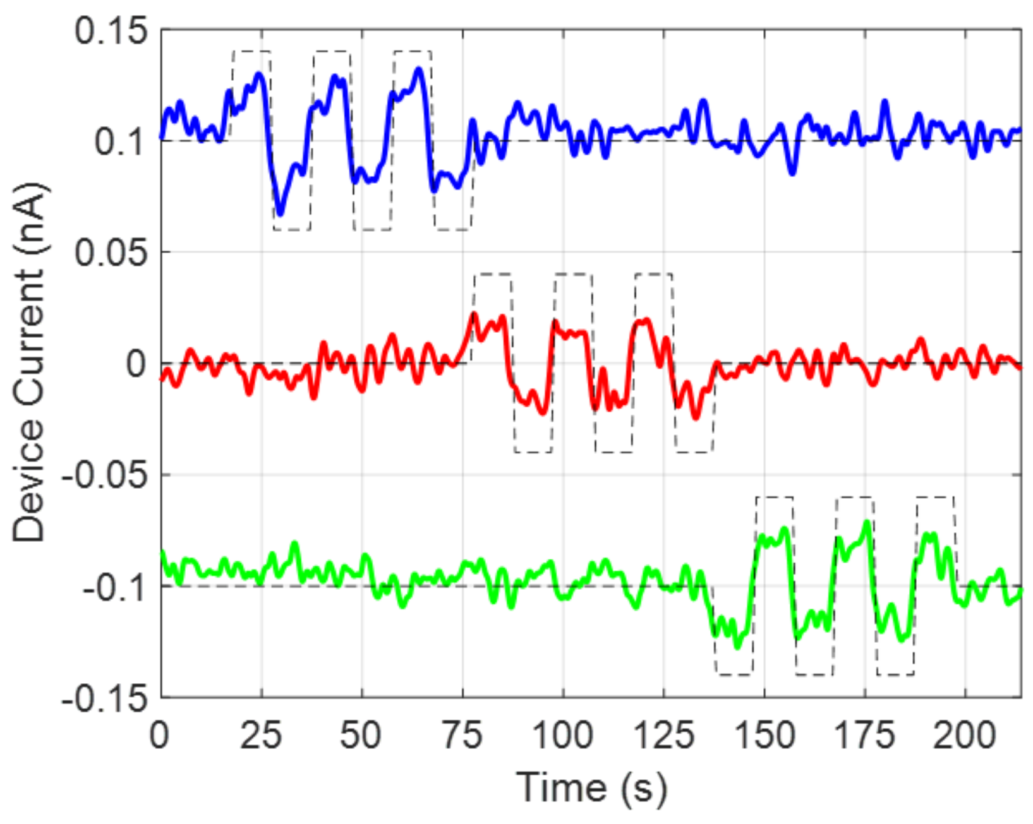
Significance/Benefits to JPL and NASA: Although we were not able to meet our single-digit nT sensitivity goal, we did make a giant stride for identifying a device geometry that produces a stable response and have improved device sensitivity by a factor of 5 from our previous best performing devices. These devices were not in any way developed for low-field magnetic field sensing, so are not too surprised the goal wasn't met. However, we are already in the process of working with external vendors to use the information gained from this study, to make a sensor ideal for very low field magnetic field sensing for science applications in space. Using isotopically purified SiC to narrow linewidth, using proton radiation to increase quantum centers, and incorporating instrumental improvements will allow us to easily reach the sub-nT sensitivity metric we seek, thereby making SiCMag competitive to heritage designs and much better than the best sensitivity of an EDMR based magnetometer reported to date, that being the 40 nT/sqrt(Hz) (Lew et al., 2023). After completing this work, JPL still maintains its position as the lead NASA center for the development of solid-state quantum magnetometers, both in electrically and optically detected methods.



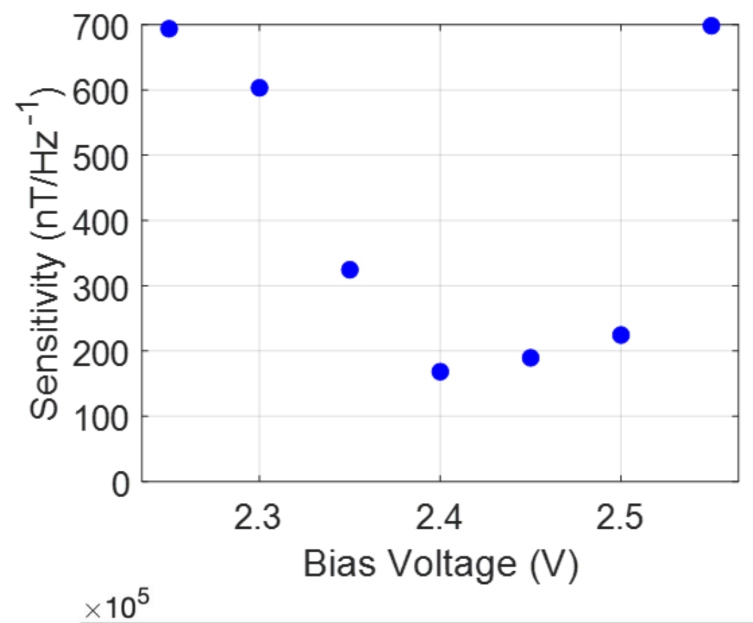
Low-field EDMR responses for two different orientations of the magnetic field with the crystalline C axis of the SiC device. The RF source used was 250 MHz.



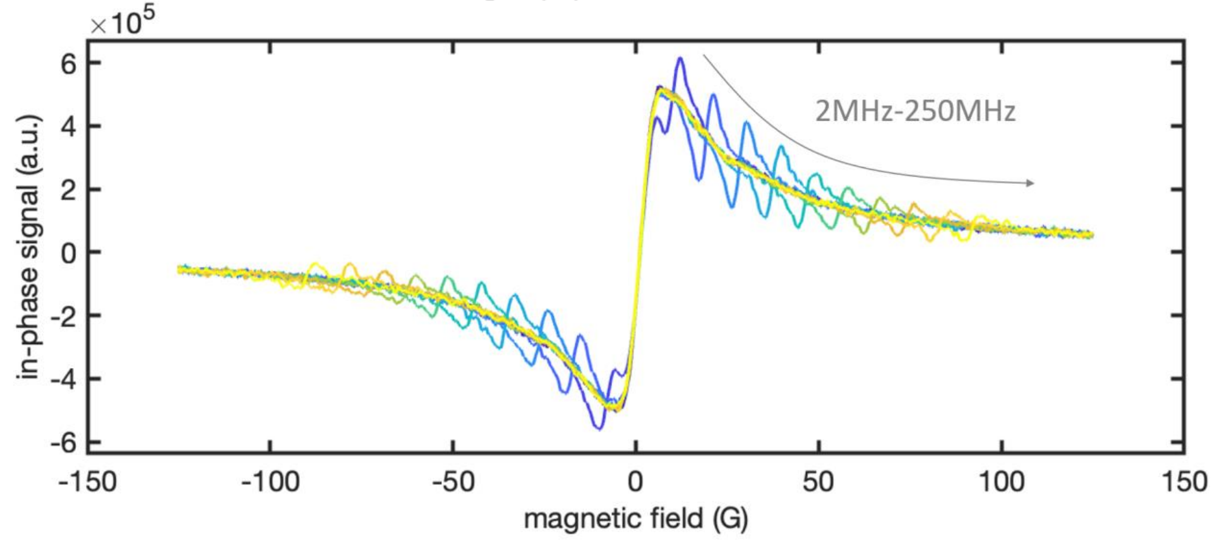
Second derivative of the low-field EDMR responses, showing the intricate electron-nuclear hyperfine interactions that are used to help characterize the quantum center.



The response of the JFET sensor when stimulated by a calibrated stimulus field with axis-alternating square waves of amplitude +/- 1 µT.



The sensitivity of the sensor response for various forward biases.



Sensor magnetoresponse for various RF fields used for absolute scalar mode. Limitations in hardware prevented us from using a RF source with frequency < 2 MHz.

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Publication in preparation. Results presented at the International Conference on Silicon Carbide and Related Materials (ICSCMR) in September 2023.

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