

University of Nebraska - Lincoln

DigitalCommons@University of Nebraska - Lincoln

Faculty Publications, Department of Physics
and Astronomy

Research Papers in Physics and Astronomy

2020

MTJ based magnetic sensor for current measurement in grid

Kai-Zhong Gao

Xiaolu Yin

Yi Yang

Dan Ewing

Paul J. De Rego

See next page for additional authors

Follow this and additional works at: <https://digitalcommons.unl.edu/physicsfacpub>

This Article is brought to you for free and open access by the Research Papers in Physics and Astronomy at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Faculty Publications, Department of Physics and Astronomy by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.

Authors

Kai-Zhong Gao, Xiaolu Yin, Yi Yang, Dan Ewing, Paul J. De Rego, and Sy-Hwang Liou

MTJ based magnetic sensor for current measurement in grid

Cite as: AIP Advances **10**, 015301 (2020); <https://doi.org/10.1063/1.5129902>

Submitted: 04 October 2019 . Accepted: 29 November 2019 . Published Online: 02 January 2020

Kai-Zhong Gao , Xiaolu Yin, Yi Yang, Dan Ewing, Paul J. De Rego , and Sy-Hwang Liou



View Online



Export Citation



CrossMark

ARTICLES YOU MAY BE INTERESTED IN

[Fabrication of soft-magnetic FeAlSi thin films with nm-order thickness for the free layer of magnetic tunnel junction based sensors](#)



AIP Advances **10**, 015302 (2020); <https://doi.org/10.1063/1.5129953>

[Exchange bias in \$\text{La}_{0.7}\text{Sr}_{0.3}\text{CrO}_3/\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3/\text{La}_{0.7}\text{Sr}_{0.3}\text{CrO}_3\$ heterostructures](#)

AIP Advances **10**, 015001 (2020); <https://doi.org/10.1063/1.5130453>

[Direct laser writing of graphene electrodes](#)



Journal of Applied Physics **127**, 010901 (2020); <https://doi.org/10.1063/1.5120056>

AVS Quantum Science

A new interdisciplinary home for impactful quantum science research and reviews

Co-Published by

NOW ONLINE



MTJ based magnetic sensor for current measurement in grid

Cite as: AIP Advances 10, 015301 (2020); doi: 10.1063/1.5129902

Presented: 8 November 2019 • Submitted: 4 October 2019 •

Accepted: 29 November 2019 • Published Online: 2 January 2020



Kai-Zhong Gao,^{1,a)} Xiaolu Yin,² Yi Yang,³ Dan Ewing,⁴ Paul J. De Rego,⁵ and Sy-Hwang Liou³

AFFILIATIONS

¹International Business and Technology Service Corporation, North Oaks, Minnesota 55127, USA

²Western Digital Corporation, Fremont, California 94539, USA

³Department of Physics and Astronomy, University of Nebraska-Lincoln, Lincoln, Nebraska 68588, USA

⁴Department of Energy's National Security Campus, Kansas City, Missouri 64147, USA

⁵Department of Energy's National Security Campus, Albuquerque, New Mexico 87106, USA

Note: This paper was presented at the 64th Annual Conference on Magnetism and Magnetic Materials.

a)Corresponding author: Kaizhong Gao, email: kaizhong.gao@intlbt.com

ABSTRACT

In this paper, the status and the challenges of utilizing MTJ based magnetic sensor for Grid sensing are reviewed. And it is shown with both modeling and experiment that an optimized MTJ based magnetic sensor can be utilized to monitor Grid current, particularly for each individual transmission line. Unlike the traditional approach, where the sensing element needs to be either integrated with, in contact with or near the transmission line, this measurement technique can be based on a contactless or a “remote” sensing setup, where the sensor is placed away from the Grid line. From the perspective of sensor, the sensitivity, the signal-to-noise ratio and the linearity of MTJ based magnetic sensor can all meet the requirement of application. It is demonstrated that an optimized DC measurement, in addition to AC measurement, can also be utilized for applications in the Grid system, such as solar energy generation.

© 2020 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>). <https://doi.org/10.1063/1.5129902>

I. INTRODUCTION

Magnetic Tunneling Junction (MTJ) based magnetic sensor has been utilized for a variety of applications, including two of the most successful applications for data storage: read head in hard disk drive and storage element for Magnetoresistive random-access memory (MRAM).^{1–4} It is extensively utilized in medical research, magnetic field sensing and rotational angle sensing.^{5–8} There are experimental demonstrations where the sensors can be utilized for electric current measurement, serving as detached or contactless current sensors.^{9–12} Due to higher sensitivity as compared to traditional Hall effect sensing, tunneling magnetoresistance (TMR) is projected to provide more applications over time despite some potential issues, such as nonlinearity, hysteresis and higher noise level.¹³ One major goal of the applications for Grid monitoring is to measure Grid current remotely in real time.¹⁴

II. MTJ BASED MAGNETIC FIELD SENSING FOR GRID

Previously, anisotropic magnetoresistance (AMR), giant magnetoresistance (GMR) and TMR based magnetic sensors were utilized to measure the electric current with the wire placed next to the sensor. Each new generation of technology provides a superior sensitivity to the measured magnetic field. Recent studies shown that it is possible to measure electric Grid condition remotely, particular for the Smart Grid.^{11–14} There are a few different conditions in terms of Grid application. AC and DC applications are both desired due to different transmission configurations in the network.

A. Initial experiment setup and modeling

In our recent work, it has been demonstrated that MTJ based magnetic sensor, named remote sensing for Grid (RemG), can be utilized to detect the Grid current in a “remote” setting, i.e. the

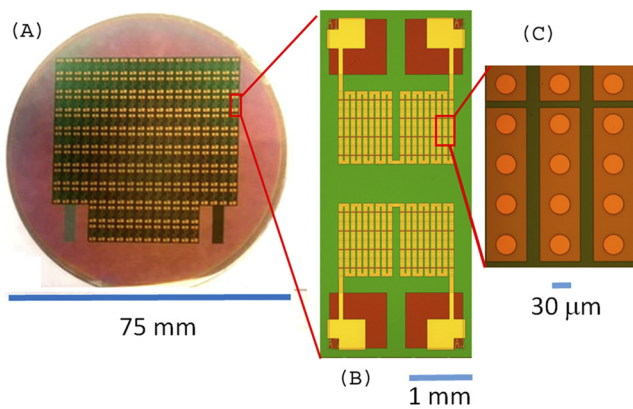


FIG. 1. (A): Top view of RemG sensors built on wafer. (B) Zoom in for each die. (C) Further zoom in for the sensing elements.

sensor is placed meters away from the Transmission line.¹⁴ Typical properties, such as magnetic transition curve, sensitivity and noise, of the MTJ sensors were investigated in detail in previous work.¹³ An MTJ sensor is built and optimized to measure the magnetic field generated by the Grid line. Fig. 1 shows the top view of the RemG sensor fabricated on wafer. In this particular application, the size of the sensor is not as extremely small as those in MRAM and HDD applications since the variation of ampere field is negligible within the space occupied by the sensor.

Compared to simulation results, a detailed model needs to be developed to obtain the value of current based on the field measurement. This is typically a reverse problem to be solved. Due to complexity of the Grid geometry or topology, different Grid structure may incur different levels of complexity from modeling. Some studies have shown, particularly for specific conditions, the modeling can be achieved quickly.¹¹ Based on our studies, one can create microcurrent model once the condition is determined.¹³ Therefore, RemG sensor can be utilized to measure Grid conditions with quick response. In one situation, where the current of a single grid line is measured, scaling can be used. And in most cases, the ampere field can be calculated based on a long wire. Thus, both measurement and modeling can be conducted in a very straightforward manner.^{14,15}

Experiment setup: For experimental demonstration, MTJ chips with in-plane magnetic anisotropy are bonded to a PCB board and a long electric wire is placed above the chips and extends parallel to the plane of the chips, such that the magnetic field generated by the current in the wire is parallel to the pinning direction¹³ of the MTJ. With a proper scaling, an in-house setup can be used to mimic the field generated by Grid line. For most of the results shown here, the particular experiment is based on 50:1 ratio scaling. The sensor response is investigated and the measured values are used to derive the magnetic field generated by the current. Note that for ampere field from a given wire, the field is proportional to the value of current. Therefore, with measurement of the ampere field perpendicular to the direction of electric current, one can extract the value of current directly once the distance from the sensor to the wire is known.

In addition, for a given configuration, the geometrical impact of the ampere field can be calculated directly before experiment is conducted.^{15,16} Since in micro current calculation, the Grid line placement is fixed in many cases, the geometric factor just needs to be precalculated once before the fitting starts and stored in the program. This approach can be compared to micromagnetic simulation, where the most time-consuming part: Demag tensor, is calculated only once, at the beginning of the program.¹⁷

B. High frequency AC measurement

As illustrated in earlier study, AC measurement has been demonstrated, where the periodic change of signal help to obtain accurate fitted results quickly.¹⁴ Previous measurements show this sensor can be utilized to measure AC waveform from the Grid using a sampling frequency at around 10 kHz.¹³ In the event of a lightning strike, an instantaneous shunt event may occur in a couple of microseconds. Thus, a higher frequency measurement is required in order to capture such an event.

Figure 2 shows when the change of current is at 10 MHz, the sampling rate of 200 M points/s can be utilized to extract the error event. Despite the current waveform changes and fluctuates over time, RemG sensor can still provide accurate measurement results that follow the waveform change. Note that with a higher sampling rate, the sensor is able to capture the error event with much more details, providing additional information to improve Grid resiliency.

C. DC measurement

Figure 3 shows the DC measurement using RemG sensor, corresponding to a distance of 1.6 meters between the sensor and the electric wire. The DC current increases by steps with an increment of 50 A. The dashed lines are modeling results, assuming that the sensor has a perfect linear response. The percentage numbers referenced here are the differences between the measurement and the modeling results.

The measurement shows a very good repeatability and indicates that for this particular case, the sensor response is almost perfectly

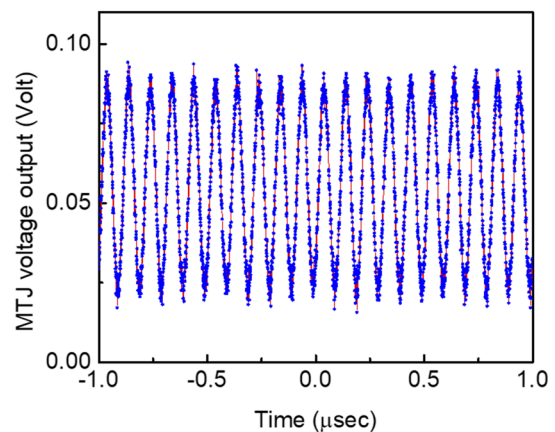


FIG. 2. Demonstration of RemG sensor for high frequency AC measurement, the sensor is placed at 1 meter away from a 200 A wire current.

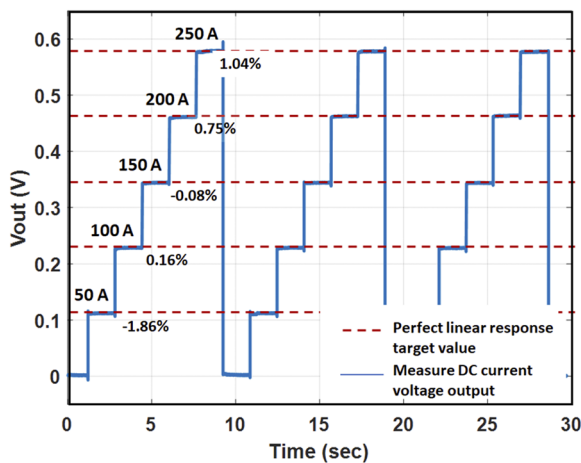


FIG. 3. DC measurement using RemG sensor, with step change in wire current vs. perfect linear response from modeling.

linear, with the maximum deviation being within 2%. In addition, the sensor will pick up small current waveform change from the current source, including the amplitude change, or under-shoot, before a step is triggered. These results show that the sensitivity of the RemG sensor is high and the response is quick. Note that for Grid application, the typical time scale is microsecond or longer, which is several orders of magnitude longer than Gyromagnetic precessional frequency. The detailed measurement shows signs of magnetic noise due to thermal fluctuation, but it is not a significant issue for this particular study. For the application in the Grid, particularly for DC measurement utilized in solar based distributed energy resources (DER), this is not a concern.

III. GRID DETECTION METRIC

A. Scaling or decay factor

From DC measurement, one can determine the decay factor to check against the assumptions utilized in the simulation, particularly for the grid geometry based pre-factor calculation. Figure 4 shows the measurement results for the field at 6 different sensor locations vs. ampere field calculation. To first order, the measured field decays with distance in an approximately $1/r$ relation, in agreement with the calculation, where the wire is assumed to be infinitely long. r is the distance from the sensor surface to the center of the wire.

A detailed study, as illustrated in the inset A), shows that the decay of the measured field does not scale with the distance by assuming an infinite long wire. There is an approximately 10% field loss when the sensor is placed further away to the wire, as compared to theory. Detailed study in the inset for log-log plot shows the decay of the field with distance is faster than $1/r$ relation by approximately 10%. Using micro current model, where the geometric factor can be taken into account numerically, the scaling with distance can be corrected. The corrected curves are shown in Fig. 4. Using our model to account for finite length of the wire that carries the current in one direction, the corrected curve matches with the experiment result. Since in most studies, measurement uncertainty is 2% or less,

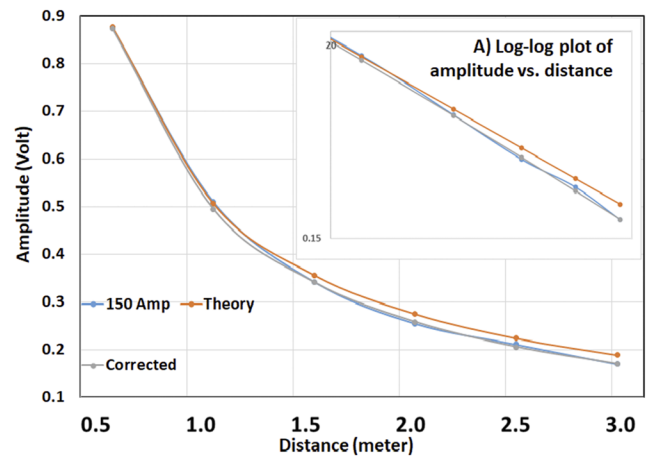


FIG. 4. Measured amplitude, theory and modeling results in voltage vs. distance from RemG sensor to the center of the wire.

the 10% difference due to geometrical factor has to be corrected in practice. With the proper model that takes into account the finite geometry of the Grid setup, the measurement and the modeling are in excellent agreement with each other.

B. Domain wall motion and hysteresis impact

One of the issues for MTJ based magnetic sensors is the hysteresis behavior in different magnetic layers on both sides of the tunneling barrier. This causes loss of both linearity and repeatability, which in many situations, limits its potential applications. In some applications, it is really hard to completely eliminate hysteresis behavior in MTJ based magnetic sensors.¹⁸ It is desired to see if such behavior will impact potential for Grid measurement. For Grid applications, the estimated field range is typically much less than one milli-tesla.

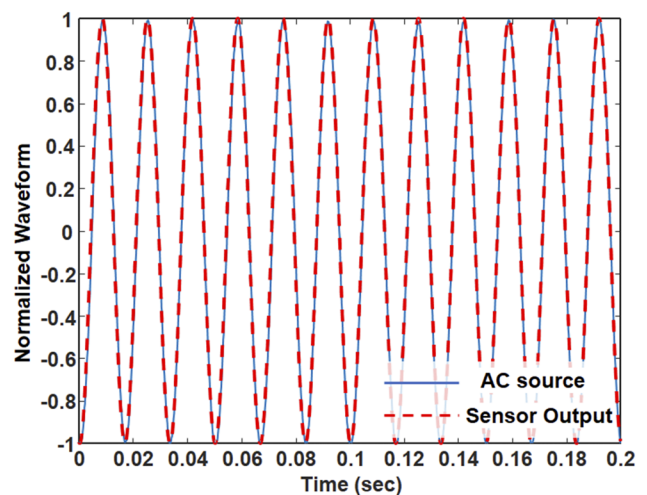


FIG. 5. Normalized measured waveform vs. current in wire. No sign of hysteresis jumps or asymmetry in response function.

Within this small range, it can be checked for an optimized sensor, whether hysteresis behavior in magnetic layers will generate error in the field measurement.

Figure 5 shows the normalized AC waveform from the wire and the measured results from the sensor response. The time delay of the response in the detection circuit has been taken into account in the figure. If hysteresis behavior impacts the measurement and the accuracy level, a difference between the measured waveform and the current waveform should be observed. The measured results show that the sensor response is almost perfectly linear and without any sign of hysteresis impact to the accuracy level. Moreover, the measurement shows no jumps induced by domain wall motions. To first order, RemG sensor can be an excellent option to monitor the Grid current.

IV. CONCLUSION

In this paper, it is demonstrated that MTJ based magnetic sensor can be optimized for Grid monitoring. Based on the field measurement, the Grid current can be extracted based on known geometry in real time. And the measurement can be done in not only AC configuration but also DC configuration. As compared to current technologies in the field,^{19,20} our technology can meet the desired accuracy level and provide useful information in a remote setting. Despite several concerns due to magnetic hysteresis and nonlinearity associated with MTJ and thin film magnetics, it is possible to use RemG technology to measure the Grid for a given situation with correct modeling approach. This technology extends the scope of spintronic applications of MTJ and may provide opportunities for another industry.

ACKNOWLEDGMENTS

This work was supported in part by the International Business and Technology Service Corporation 201904001 sensor technology initiatives. Prior work received support from Honeywell Federal Manufacturing & Technologies. The MTJ samples were prepared in the Nebraska Nanoscale Facility: National Nanotechnology Coordinated Infra-structure and the Nebraska Center for Materials and Nanoscience, which are supported by the National Science Foundation under Award NNCI-1542182, and the Nebraska Research

Initiative. Dr. Kaizhong Gao wants to acknowledge Mr. Mark Ahlstrom for his valuable comments on the Grid applications.

REFERENCES

- ¹M. Igami and K. Uetake, SSRN (2019).
- ²S. Mao, Y. Chen *et al.*, *IEEE Trans. Magn.* **42**(2), 91 (2006).
- ³Everspin pilot production of 1Gb spin transfer torque MRAM, June 2019, <https://finance.yahoo.com/news/everspin-enters-pilot-production-phase-120000858.html>.
- ⁴K. Z. Gao, talks at google, Feb. 2018, <https://www.youtube.com/watch?v=nEUf4fMSwMc&t=101s>.
- ⁵S. X. Wang and G. Li, *IEEE Trans. Magn.* **44**(7), 168701702 (2008).
- ⁶J. Amaral and P. P. Freitas, "Integration of TMR sensors in silicon microneedles for magnetic measurements of neurons," *IEEE Trans. Magn.* **49**(7), 3512–3515 (2013).
- ⁷P. P. Freitas, R. Ferreira, S. Cardoso, and F. Cardoso, *J. Phys.: Condens. Matter* **19**, 165221 (2007).
- ⁸R. Slatter, *Proceedings SENSOR*, 2015, pp. 228–233.
- ⁹Y. Ouyang, J. He, J. Hu, G. Zhao, Z. Wang, and S. X. Wang, *IEEE Trans. Magn.* **51**(11), 4004204 (2015).
- ¹⁰C. Zheng, K. Zhu, S. C. Freitas, J. Y. Chang, J. E. Davies, P. Eames, P. P. Freitas, O. Kazakova, C. G. Kim, C. W. Leung, S. H. Liou, A. Ognev, S. N. Piramanayagam, P. Ripka, A. Samardak, K. H. Shin, S. Y. Tong, M. J. Tung, S. X. Wang, S. S. Xue, X. Yin, and P. W. T. Pong, *IEEE Trans. Magn.* **55**(4), 0800130 (2019).
- ¹¹Q. Huang, Y. Song, X. Sun, L. Jiang, and P. W. T. Pong, *IEEE Trans. Magn.* **50**(7), 0900107 (2014).
- ¹²X. Sun, K. S. Liu, K. K. Y. Wong, W. K. Lee, Y. Hou, Q. Huang, and P. W. T. Pong, *IEEE Trans. Magn.* **47**(10), 2608 (2011).
- ¹³X. Yin, Y. Yang, Y. F. Liu, J. Hua, A. Sokolov, D. Ewing, P. J. De Rego, K. Z. Gao, and S. H. Liou, *Proc. SPIE* **11090**, 110903H (2019).
- ¹⁴K. Z. Gao, US provisional patent application, 2019, K. Z. Gao and S. H. Liou, Electricity Industry Technology and Practices Innovation Challenge (EIT-PIC) Tier II Gold Award, US Department of Energy, Aug. 2019, press release.
- ¹⁵T. WEILAND, *International Journal of Numerical Modelling* **9**(4), 295–319 (1996).
- ¹⁶K. Z. Gao and H. N. Bertram, *IEEE Trans. Magn.* **38**(6), 2063–2065 (2002).
- ¹⁷D. Wei, S. Wang, Z. Ding, and K. Z. Gao, *IEEE Trans. Magn.* **45**(8), 3035–3045 (2009).
- ¹⁸X. Yin, Y. F. Liu, D. Ewing, C. K. Ruder, P. J. Rego, A. S. Edelstein, and S. H. Liou, *Proceedings of SPIE* **9551**, 95512N (2015).
- ¹⁹Y. Liu, L. Mili, J. De La Ree, and R. F. Nuqui, CiteSeerX 10.1.1.2.7959 (2001).
- ²⁰T. Rizy, US DOE GMLC Review and Assessment of Sensing and Measurement Technology for Electric Power Grids, Feb. 2019, <https://gridmod.labworks.org/resources/review-and-assessment-sensing-and-measurement-technology-electric-power-grids>.