Next Generation of Magnetic Field Control for MRAM and Magnetic Sensor Device Testing

May 2, 2022

Introduction

With the widespread expansion of magnetically-operating devices such as Magnetic Sensors and Magnetic RAM (MRAM), capital equipment suppliers must develop test equipment that provides reliable and accurate magnetic field control. Since release of their first magnetic device tester in 1996, Integral Solutions International, ISI, with corporate headquarters in the heart of Silicon Valley, has been at the forefront of meeting these technological requirements. This paper discusses solutions to the challenges faced in the design and implementation of electromagnets and measurement systems intended for testing magnetic devices at wafer level.

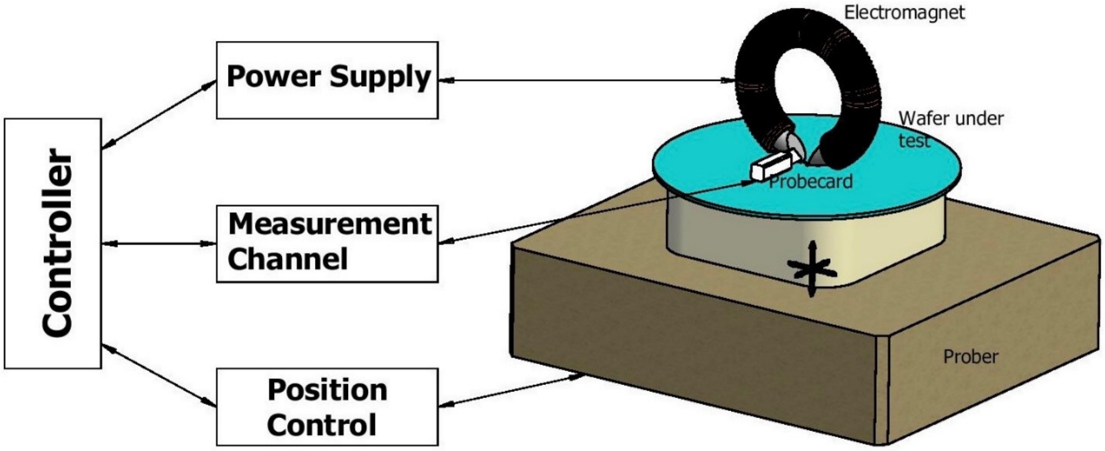

Figure 1. Typical components of magnetic-device test equipment at wafer level

Projected-Field Electromagnet Design

Magnetic field generating systems developed by equipment companies such as ISI can be generalized by 3 primary components: a controller, a power supply, and an electromagnet. The controller controls the power supply to generate a certain current to the electromagnet, which in turn generates a magnetic field to the device under test (DUT). Separately, a set of measurement equipment, most commonly for measuring resistance, synchronized with the controller is electrically connected to the DUT, such as with a probe-card, to measure the performance of the DUT while it is being subjected to this external magnetic field. For DUT devices such as wafers a robotics system such as a prober may be incorporated, for loading each wafer and positioning each set of DUTs on the wafer with respect to the probe-card and electromagnet. These components form the basis of all magnetic-device test equipment (see **Figure 1**).

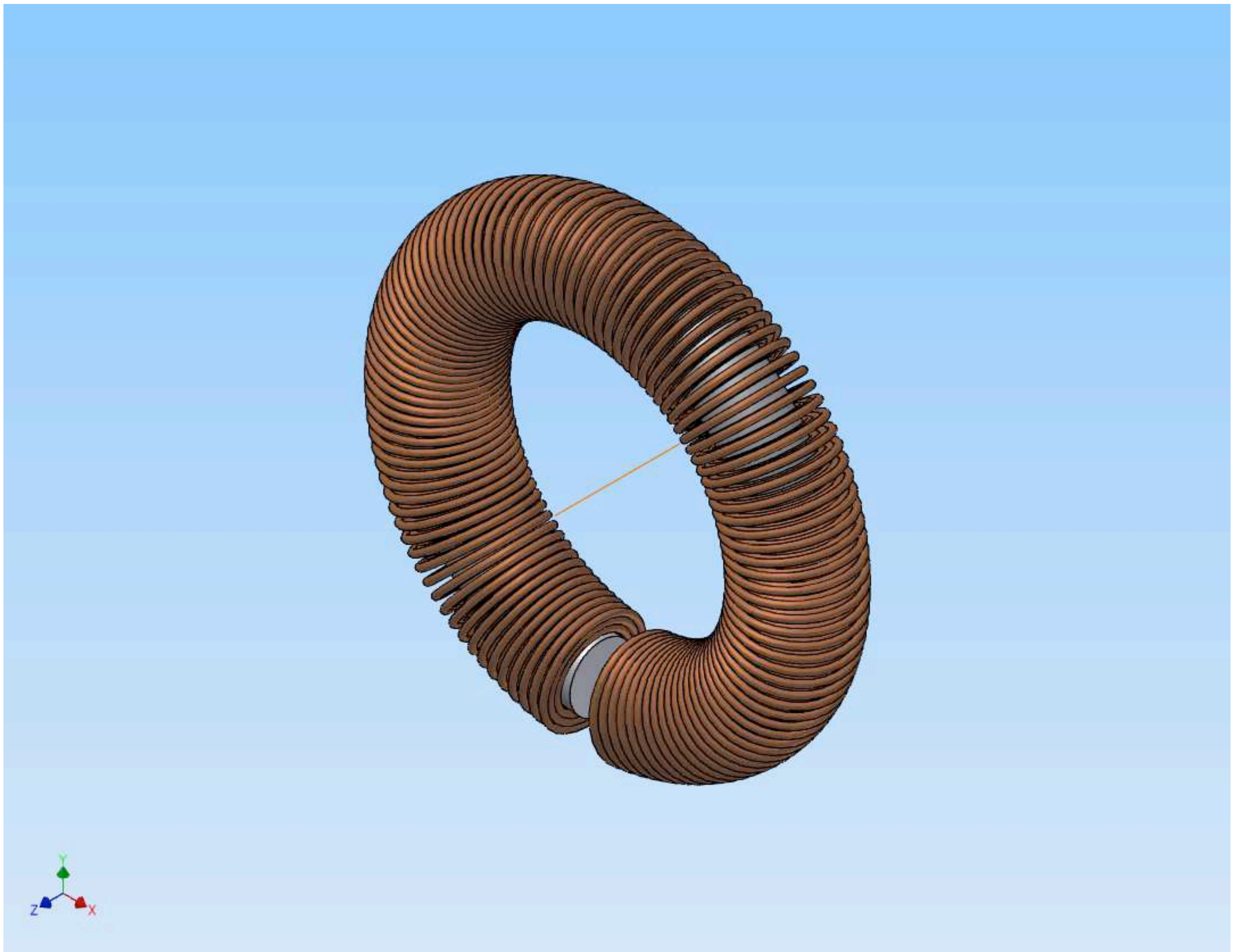

Figure 2. Typical “C” Core magnet (shown with metal core)

Of critical importance to the success of this system is the magnet design. In simplest form the electromagnet may just be a wound coil, or set of coil windings, that generates a magnetic field in proportion to the magnitude and polarity of the supplied current. In practice, this design, often referred to as “air core” due to the absence of ferrous material used within the coil windings, is limited in both the magnitude and orientation that the magnetic field can be produced. The most common solution to overcome these limitations is to wrap the coils around a ferromagnetic core made of material with high magnetic permeability, such as iron (see **Figure 2**). The high permeability of the core material, compared to the surrounding air, greatly magnifies the density of the magnetic field, while also directing this field to flow through the material in a geometrically controlled manner. An ideal configuration would be a round core with a relatively small gap cut out of it, essentially in the shape of a C with 2 or more poles, and with windings around the remaining core material. Dependent on the dimensions and width of the gap the magnetic field within this gap can be orders of magnitude higher than the field produced by the same coil without a core, along with the added benefit that the core physically guides the magnetic field to a desired target location (see **Figures 3A and 3B**). Placing the DUT within the poles of this gap provides an ideal configuration for measurement.

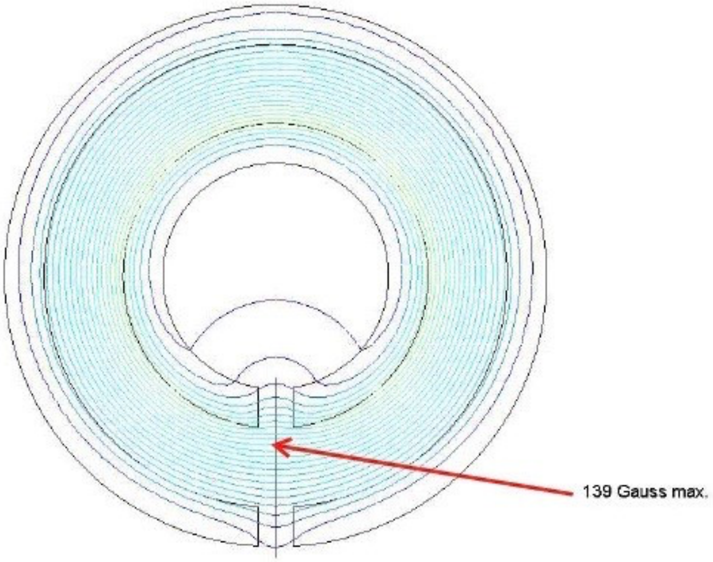

Figure 3A. Typical “C” Core magnet with Air Core.
Maximum magnetic field in gap center limited to 139 Gauss.

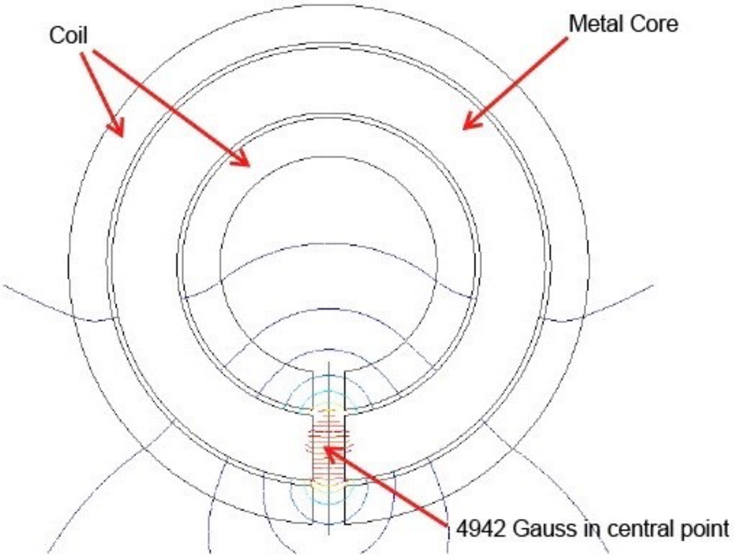

Figure 3B. Same coil as in Figure 3A, but wound around a metal core.
Maximum magnetic field in gap center increased to 4,942 Gauss.

Unfortunately, because MRAM and Magnetic Sensor devices are typically tested at wafer level, using conventional probing stations where the wafer is carried on a chuck assembly, the large diameter of the wafer and inaccessible area below the wafer makes it physically incompatible with the traditional C-core electromagnets described above. For wafer test applications it has been necessary to develop electromagnets that project a magnetic field towards the wafer surface. This configuration has similar deficiencies to air core magnets, in that much of the magnetic field strength is lost over the air-gap distance between the pole-tips and the wafer surface, and there is a difficulty in geometrically directing this magnetic field to the measurement area of interest on the wafer.

Another side-effect of this projected-field configuration is the volume of the projected uniform field. With the C-core configuration, dependent on the dimensions of the poles vs. the gap the magnitude of the magnetic field can be highly homogeneous over a certain volume of space (see **Figure 4A**). Typically defined in terms of volume (in mm^3) with +/-1% variation, this homogeneous area is referred to as the Uniform Field Zone. With a projected-field the magnitude of the field rapidly dissipates as a function of increased distance from the poles, making homogeneity a difficult task (see **Figure 4B**). With the generally higher field requirements that customers demand, the projected field volume is typically small, due to constraints in having to maximize the magnitude of the projected field by compressing it over a relatively small area. Complex modelling and design must be implemented to maximize the volume of the Uniform Field Zone on projected-field electromagnets, while also optimizing this projected field for highest magnitude. Since this projected field rapidly dissipates as a function of distance from the pole-tips, it is incumbent on the tool developer to quantify the target testing location and homogeneous region, and assure that the DUT will be placed within this region, otherwise there will be an error between the desired magnetic field and the actual field seen by the DUT.

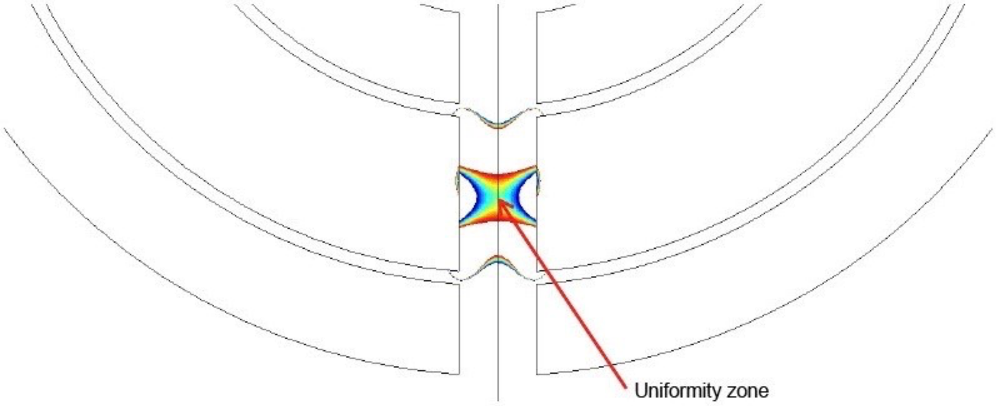

Figure 4A. “C” Core magnet with internal uniform field

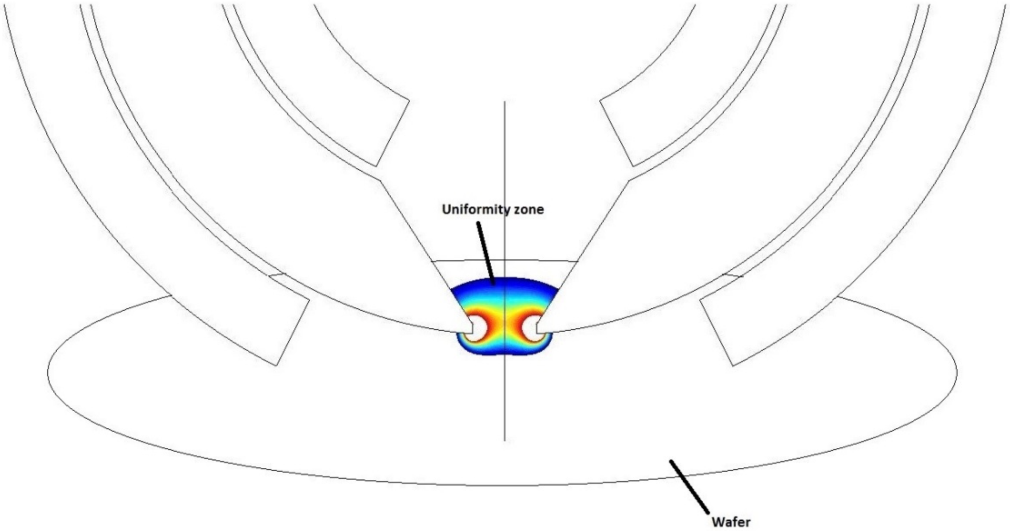

Figure 4B. "C" Core magnet with projected uniform field, projecting the uniform field zone to a small but predictable volume at the wafer surface

An additional side-effect of core-based electromagnets is hysteresis. While various core materials may be magnetically permeable, they will have different levels of coercivity. With lower coercivity the core material will have lower magnetic field remanence after the current to the coil has been changed or removed. This field remanence and higher coercivity directly translates to hysteresis, resulting in an undesirable offset error between the target vs. actual magnetic field. Specially treated and manufactured core materials do exist that have low remanence, but unfortunately also have relatively low core saturation. So while projected-field electromagnets can be made from low coercivity materials, they are generally hindered by somewhat low maximum field potential due to saturation (see **Figure 5**).

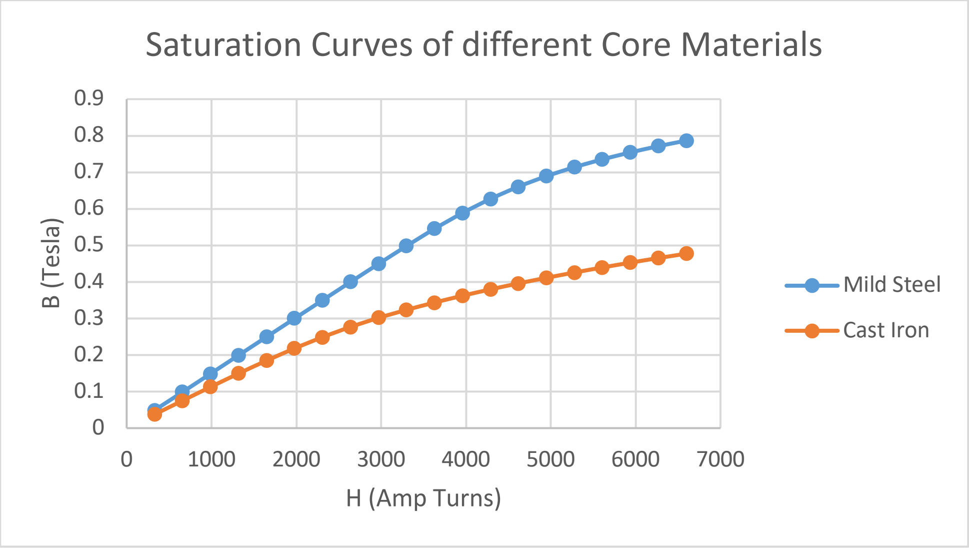

Figure 5. Saturation Curves of various core materials

Additionally, while core saturation is a parameter of magnetic materials, saturation is also greatly influenced by the volume of the core material. This is especially troublesome in the design of projected-field magnets, as several key factors conspire to compromise an optimal design. These factors include maximizing the field strength, optimizing the Uniform Field Zone, desired orientation of the field, space allowance for probe-cards, and space for optical viewing of the DUT during probing. Addressing these factors results in the pole-tips of projected-field magnets generally having much smaller cross-sectional areas compared to the main core. Unfortunately, making these pole-tips small makes them susceptible to premature saturation, ultimately altering the magnitude, position, and homogenous volume of the produced field. All things considered the tool designer must design the pole-tips with as large of volume as possible and predict how saturation will impact the measurement field if the magnet is designed to operate beyond its linear region.

Closed-loop controllers can be implemented to compensate for hysteresis and saturation, but these mechanisms are at a disadvantage with projected-field electromagnet designs. Ideally, the feedback sensor of the closed-loop controller will be positioned exactly where the DUT will be placed, or at least within close proximity. With internal magnets this is possible, since the Uniform Field Zone is large enough to allow both the DUT and field sensor to coexist. But in a projected-field design the uniform field is small, and the DUT and probe-card both occupy this valuable space, requiring the feedback sensor to be positioned elsewhere. Great care must then be taken to assure that the closed-loop controller maintains the proper field at the DUT test location even under various hysteresis and saturation conditions.

Along the same lines as hysteresis, eddy currents and inductive pickup similarly impact magnetic device testing by altering the produced and sensed magnetic fields during AC excitation of the coil. Unlike hysteresis and saturation, managing issues like eddy currents can be a difficult challenge for magnetic test equipment designers to overcome, since components like the probe-card and the DUT itself often contribute to the magnitude of these parasitics.

Further, the methodology for taking the measurement samples during a field sweep greatly contribute to the impact of these parasitics. Conventionally, the magnetic field may be swept continuously, at some defined frequency and magnitude, while the controller samples the DUT (see **Figure 6A**). Independent on whether the magnet is cycled with a triangle or sine waveform, parasitics including hysteresis, eddy currents, and inductive pickup will produce an offset of the B(H) measurement field at the DUT (see **Figure 6B**), resulting in measurement error. Further, varying the operation of the magnet, such as basic user-defined parameters such as changes to amplitude or frequency, will produce different offset values and corresponding measurement errors. It is imperative that the tool designer account for these variations when considering the relationship between magnet operation and measurement methodology.

Conventional Field Control and Measurement Sampling Methodology:

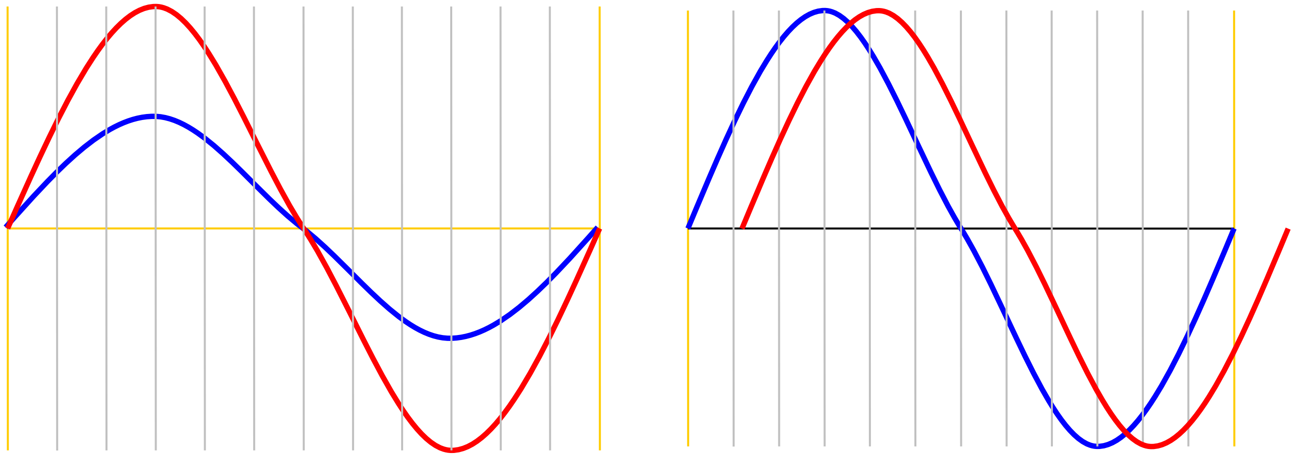

Figure 6A. Single excitation frequency with two field amplitudes shown. Fixed sampling rate results in variable resolution.

Figure 6B. Measurement error due to hysteresis, eddy currents, inductive pickup, and other parasitics caused by AC field excitation.

Oversampling is another consideration related to magnet control and measurement technique. Oversampling is very useful in reducing the "noise" of the measurement, improving measurement accuracy. Conventional field control, where the magnet is operated with a continuously varying sweep, inherently does not lend itself well to oversampling. The best that can be achieved is by averaging several adjacent samples that are roughly at the same field. Historically, though, the most common practice of oversampling is by averaging, by calculating the average measurement response of the DUT over N cycles. Unfortunately this type of averaging methodology has an inherent flaw, not taking into account the fact that magnetic device under test may and likely will not exhibit identical behavior over multiple sweeps. By "averaging" each of these individual sweep curves to produce a single result any non-linear behavior and other interesting features that do not repeat at the exact same field will be suppressed. In other words, by enabling averaging in order to improve the measurement resolution, the specific non-linear jumps you may be looking for will ultimately be diffused (see **Figures 7A-7C**).

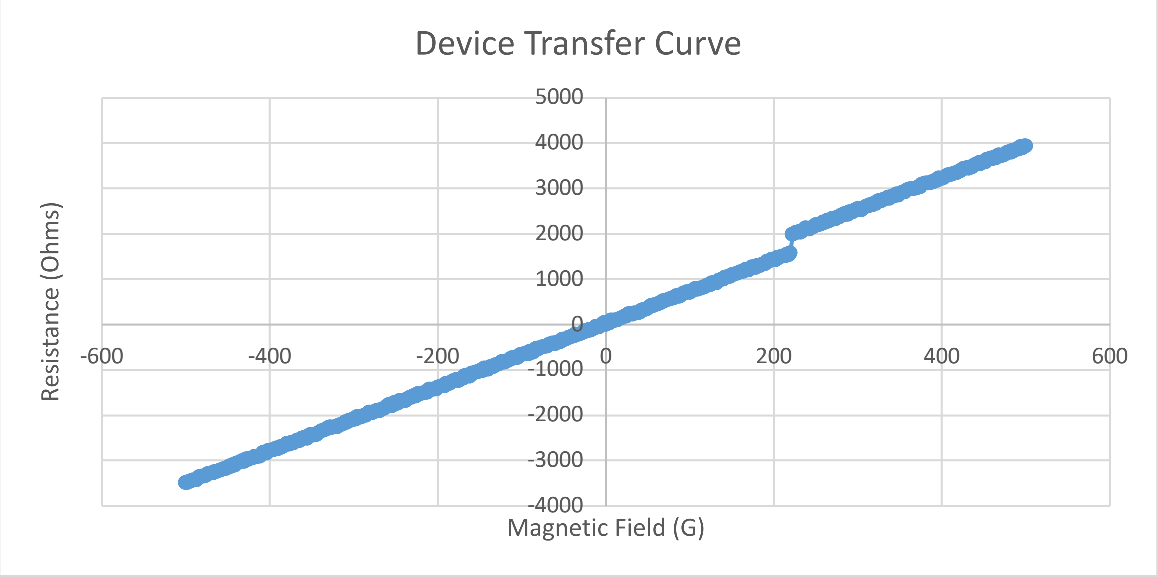

Figure 7A. Transfer Curve of device with magnetic instability.

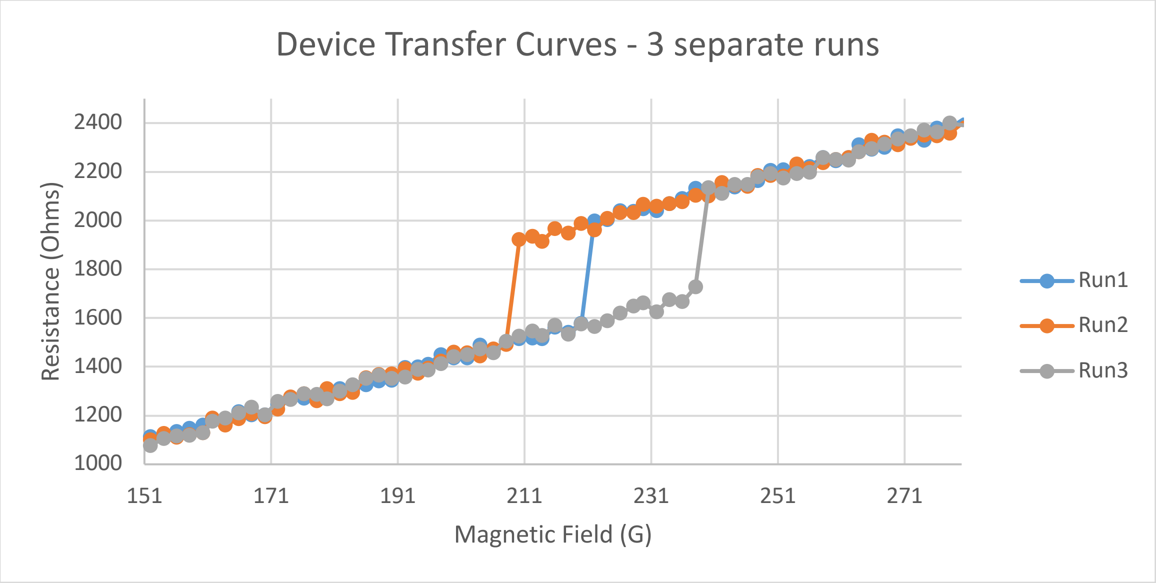

Figure 7B. 3 runs of this same device, zoomed in to show the variability of the field location that induces this instability.

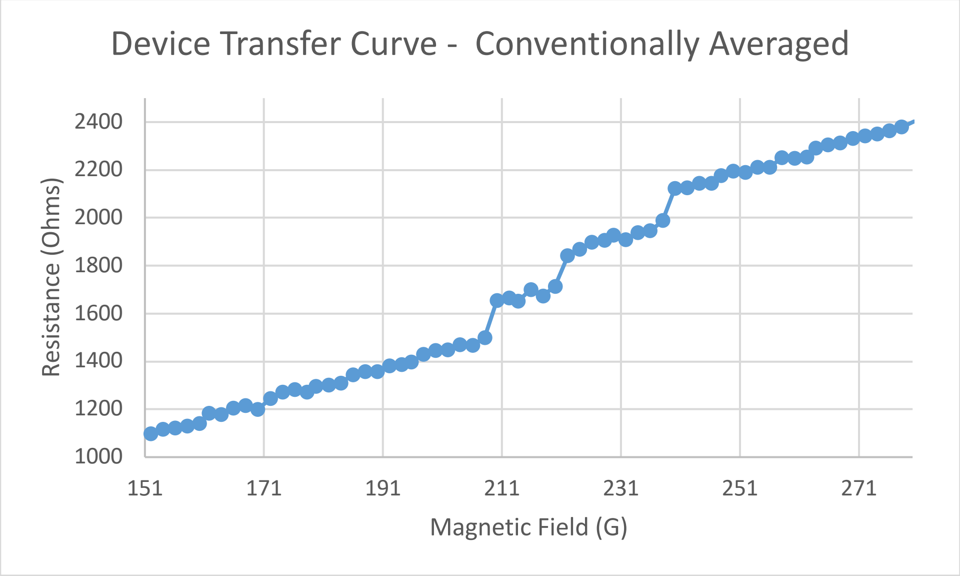

Figure 7C. Conventional averaging technique, averaging all 3 runs with intention of reducing noise and increasing measurement accuracy. Unfortunately all non-linear behavior of this device has been suppressed in this averaged curve.

With all these factors contributing to an error between the expected vs. actual projected field seen by the DUT, magnetic field calibration becomes a huge concern. If the tool allows pole and core configuration, probe-pin height and position adjustability, or magnetic field frequency and amplitude control; or if the magnet is intended to operate into saturation, has relatively small pole-tips, or is made from a material with relatively high coercivity; or if the magnet is allowed to be repositioned relative to the DUT, such as from thermal expansion due to heating and cooling under operation; or if the DUT is offset from the center of the poles, within or outside of the Uniform Field Zone; all of these factors impact the resulting field at the DUT. Calibration can become extremely burdensome for the end-user, and ultimately irreproducible, if the tool has not been designed with these considerations in mind.

Lastly, not every customer desires the same magnetic field orientation. The MTJ element on most STT-MRAM devices require only a perpendicular orientation of magnetic field to be applied to the DUT. Currently, SOT-MRAM devices require at least 2 axes of field, a perpendicular field similar to the STT-MRAM requirement, along with an in-plane field providing an assistance for write switching operations. Further, while most MRAM devices require only 0.5T of maximum field, advanced R&D applications may require maximum fields as high as 1.5T. Comparatively, magnetic sensor testing generally require 2D in-plane or 3D X/Y/Z fields, with flexibility of controlling the angle of the field vector within this 2D or 3D space. As a tool designer, not only must a system be implemented to handle these various configurations, but different physical magnets must be designed to optimize the system's operation for each challenge. It would be ideal if tool suppliers offered kits to convert any system between magnet configurations with relative ease.

The Ideal Magnetic Testing Solution – ISI WLA5000 with 1D, 2D, and 3D Field Control

With decades of experience ISI, has developed turnkey systems that address all of these concerns.

To resolve remanence and hysteresis, for electromagnets generating fields up to 0.5T ISI developed a proprietary core using an alloy with a very high saturation level and extremely low remanence. Using this unique alloy core, ISI's proprietary magnets provide high field accuracy, low hysteresis, predictable saturation profile, and core remanence of approximately 1 Gauss or less. In support of even higher magnetic fields, up to 1.5T, a new core design has been developed. To address the issues of both saturation and hysteresis ISI further developed a proprietary closed-loop controller, protected under US Patent #7550967. Utilizing this proprietary controller hysteresis, remanence, and saturation issues are compensated while providing customers the significantly higher field capability of this new core design.

Along with this patented controller, to optimize the system for the fastest magnet cycling possible ISI developed their own bipolar power supply. Rather than relying on off-the-shelf universal units, this proprietary power supply was designed to match with ISI's electromagnets, providing the most precise magnetic field operation commercially available. Along with this performance and speed, a host of protection and safety features were implemented including hardware systems for monitoring overheating, over-resistance, and over-current, and the QPX power supply unit comes with Semi-S22 compliance.

Since the release of the first commercial magnetic-device wafer level tester in 2009 and the first commercial MRAM tester in 2012, ISI has developed 5 different electromagnet configurations to meet the needs of their customers (see **Table 1**). All of these magnet assemblies are designed to be user-interchangeable in under 1 hour. For higher-field magnets, combined with the capability of the ISI WLA5000 system, a controlled rate of cooling air is provided to maintain the magnet at a stable temperature, avoiding field positioning issues related to thermal expansion. By design this cooling system is fully-contained, such that air is not allowed to exhaust towards the wafer.

Magnet	Max X	Max Y	Max Z	Remanence	Calibration	Uniformity (+/-1%)
QuadPole Inplane	0.3T	0.3T	N/A	<1G	Factory	1mm x 1mm x 0.1mm
0.5T Perpendicular	N/A	N/A	0.5T	<1G	Factory	0.8mm x 0.8mm x 0.25mm
1T Perpendicular	N/A	N/A	1T	<15G*	Factory	6mm x 6mm x 0.1mm
1.5T Perpendicular	N/A	N/A	1.5T	<15G*	Factory	2mm x 2mm x 0.1mm
3-Axis	0.1T	0.1T	0.5T	<1G	Factory	2.4mm x 2.4mm x 0.1mm

* closed-loop mode under US Patent #7550967

Table 1. Electromagnet Options for the ISI WLA5000 Wafer Tester

To address the concerns about Uniform Field Zone, ISI's electromagnets are designed to maximize the volume of this homogeneous field, and maximize the cross-sectional area of the pole-tips, while also maximizing projected field strength. Extensive modelling and development have been performed in the design of these poles and pole-tips. Of equal importance, ISI's electromagnets are reconfigurable, rather than adjustable, meaning a finite set of configurations. Lastly, ISI systems are designed to operate at a specific probing depth with respect to the poles of the magnet. This methodology, accomplished by developing their own probe-card PCBs and mechanics, assures that the probing location will always be within the target measurement region. Under these technological principles the

ISI systems are designed to have known and predictable field magnitude and geometry at the target DUT measurement location.

To address the concerns of eddy currents and other AC-related parasitics, ISI developed a different methodology for sweeping of the magnetic field. Compared to conventional methods shown in **Figures 6A-6B** earlier, rather than sweeping the magnetic field continuously ISI's methodology is to build the sweep curve from a series of single, short, quantifiable steps. After each step the DUT and channel are allowed to settle prior to the measurement being taken (see **Figures 8A/8B**). In doing so, any inductive pickup or eddy currents will be minimal, in part because the step size is small, and further because these parasitics will be allowed to dissipate prior to the measurement being taken. The entire sweep is then built from a series of these predictable steps, with flexibility to control the sweep magnitude, frequency, and overall waveform in essentially whatever manner the user would like. To accommodate this methodology ISI's proprietary power supply was optimized for small-step performance, with ability to perform an entire sweep down to one second or less.

ISI Field Control and Sampling Methodology:

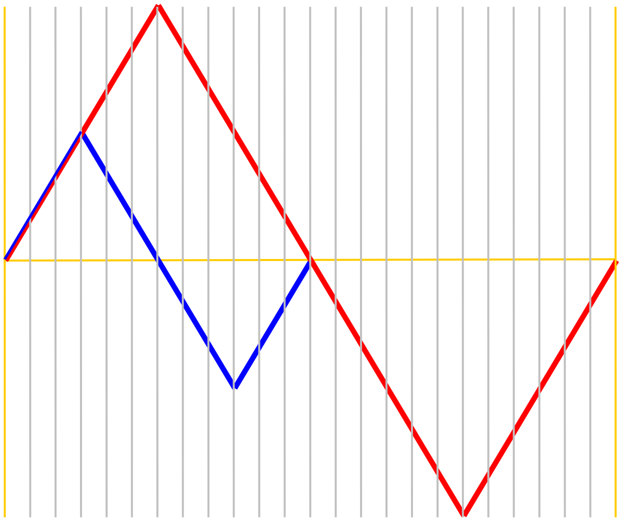

Figure 8A. Single sampling rate at linearized magnetic field

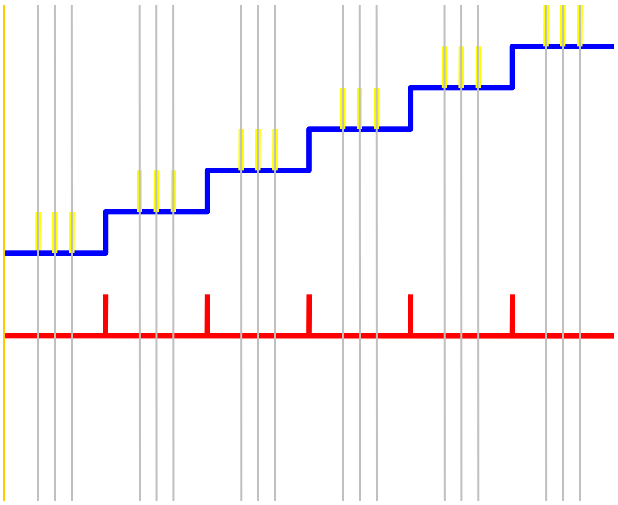

Figure 8B. Unlike the technique shown in Figures 6A/6B, ISI measurements are accurately performed after each field step has settled; oversampling (ex. 3x) possible

Under ISI's measurement methodology, for noise reduction and improved measurement accuracy the user may also configure the system to oversample the measurement while the magnet remains at each of these individual field-step levels. In comparison to averaging multiple sweeps to generate a single curve shown previously in **Figure 7C**, the ISI technique preserves the features of each individual cycle while also allowing oversampling for noise reduction (see **Figure 9**).

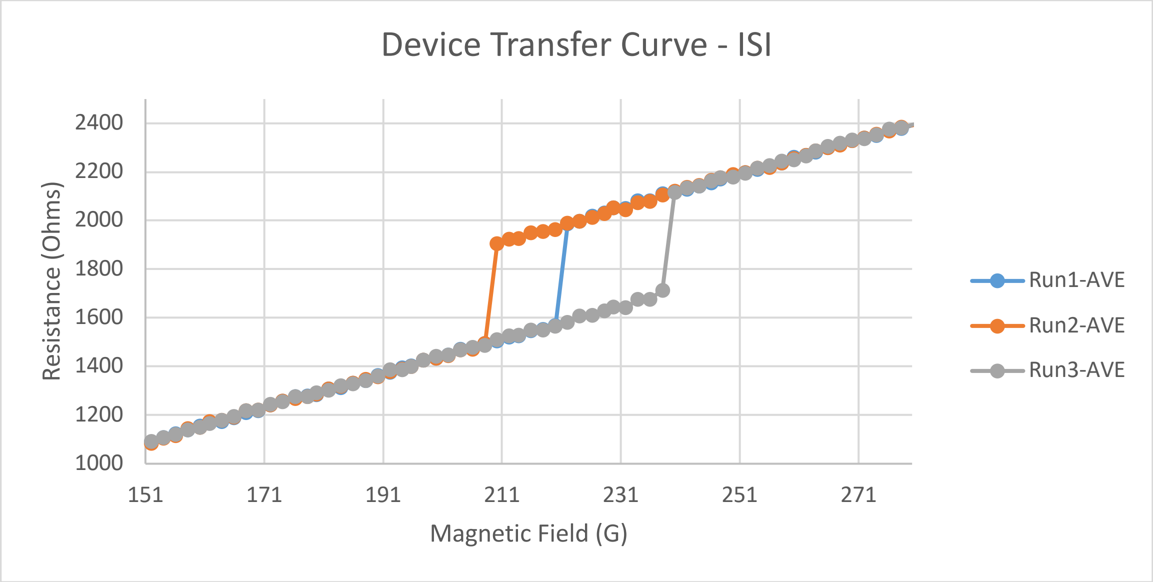

Figure 9. ISI measurement technique including oversampling.
Unlike the averaging technique shown in Figure 7C, non-linear behavior of the device has been empirically preserved while oversampling reduced noise, providing the highest level of measurement accuracy.

Lastly, under ISI's comprehensive approach all concerns related to magnet calibration are eliminated. Since ISI's field sweep consists of a set of measurements performed at incremental DC fields, the behavior of these incremental steps is essentially the same as if each of these fields was applied directly. As example, the incremental step of 255 Gauss produced during a field sweep from 0 to 500 with increment 5 will be equivalent to the 255 Gauss of field produced if the system was simply commanded to generate that single DC value. Combined with the fact that the ISI tester maintains a fixed distance between the poles and the measurement location, since the field sweep is essentially a series of predictable DC field increments the magnetic field produced by ISI tester can be factory-calibrated one time under DC operation at the center of this DUT test position, without need for the customers to have to recalibrate.

Figure 9. The ISI WLA5000 Wafer-Level Tester, shown here mated with an Accretech UF3000 Prober

In the end, ISI has developed a predictable system, the WLA5000 (see **Figure 9**), where customers can swap devices, probe-cards, pad layouts, wafer maps, field waveform patterns, field magnitudes, and field frequencies, without any further recalibrations, maintenance, or concerns by their users. Just load in a new probe-card and press START.

Conclusion

When operating a magnetic test tool, the following key questions should be considered:

- What magnetic field will be achieved as a function of distance from the pole-tips of my projected-field magnet, especially if the distance between poles and wafer is allowed to vary?
- How does the volume of uniform field zone change with respect to the distance between my wafer and the poles?
- How will this field be influenced by material and pole saturation, further complicated by adjustable distance between poles and DUT?
- Will my DUT influence my magnetic field?
- Is oversampling possible, or am I required to average multiple curves in order to achieve a low-noise result?
- How will magnetic hysteresis and eddy currents impact my magnetic field and measurement result, for example if I ran my magnet at 10Hz and 500 Gauss vs. 1Hz at 5000 Gauss, or any other combination?
- Does my system produce a remanent field?
- What are the impacts to my magnetic field if I ran a sine vs. triangle waveform?
- How can I be assured my DUT is seeing the intended field if I mechanically reconfigure my poles, change probing height, change cycle frequency, change field magnitude, etc.?
- How often, and under what circumstances, do I need to recalibrate my system?

And another extremely important question. If I have 2 systems, will they correlate with each other?

Through years of effort ISI has developed a solution that satisfies all these concerns. The ISI systems are designed to be factory-calibrated and maintenance-free, relieving a huge burden from their customers. And as tool developers, ISI has made it a priority that their systems will absolutely correlate with each other, under the least amount of user interaction. It is for these reasons ISI continues to be the trusted resource for both R&D and inline magnetic device testing by several top-tier customers, with more than 1000 ISI testers shipped worldwide.