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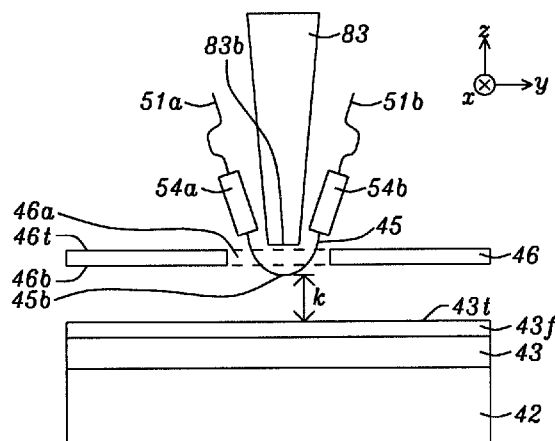


FIG. 5

(57) Abstract: A ferromagnetic resonance (FMR) measurement system is disclosed with a waveguide transmission line (WGTL) connected at both ends to a mounting plate having an opening through which the WGTL is suspended. While the WGTL bottom surface contacts a portion of magnetic film on a whole wafer, a plurality of microwave frequencies is sequentially transmitted through the WGTL. Simultaneously, a magnetic field is applied to the contacted region thereby causing a FMR condition in the magnetic film. After RF output is transmitted through or reflected from the WGTL to a RF detector and converted to a voltage signal, effective anisotropy field, linewidth, damping coefficient, and/or inhomogeneous broadening are determined based on magnetic field intensity, microwave frequency and voltage output. A plurality of measurements is performed by controllably moving the WGTL or wafer and repeating the simultaneous application of microwave frequencies and magnetic field at additional preprogrammed locations on the magnetic film.

SCANNING FERROMAGNETIC RESONANCE (FMR) FOR WAFER-LEVEL CHARACTERIZATION OF MAGNETIC FILMS AND MULTILAYERS

TECHNICAL FIELD

The present disclosure relates to a system for measuring magnetic properties in magnetic films and multilayers, and a method for doing the same, and in particular, to a waveguide transmission line (WGTL) that is mounted on a platform and installed in an electrical probe station to enable fully automated FMR testing across entire wafers without a need to cut the wafers in engineering or product environments.

BACKGROUND

Magnetic thin films and multilayers play a key role in various types of magnetic storage devices such as a magnetic hard disk (HDD) drive, Magnetic Random Access Memory (MRAM), spin torque oscillator (STO), and magnetic domain wall devices. In order to develop and optimize such devices, characterization of magnetic thin film stacks is necessary. A variety of different magnetic characterization techniques must be used to determine all the essential magnetic parameters such as crystalline anisotropy, surface or interface anisotropy, magnetization saturation (M_s), damping constant (α), gyromagnetic ratio (γ), inhomogeneous broadening, resistance x area product (RA), and magnetoresistive ratio (MR).

FMR is a well-established method of measuring anisotropy fields, as well as the gyromagnetic ratio γ , and the damping constant α of magnetic films and multilayers in extended unpatterned films or in sub-micron patterned structures. The resonance frequency f_R of a ferromagnetic film is given by the so-called Kittel formula shown in equation (1) below where H_R is the resonance field applied perpendicular to the plane of the film, H_K is the effective anisotropy field which includes structural, surface, and magnetostatic contributions, and γ is the gyromagnetic ratio.

$$2\pi f_R = \gamma (H_R + H_K) \quad (\text{Eq. 1})$$

A FMR experiment is performed by probing the magnetic system (thin film, multilayer stack, or structured device) with a combination of microwave excitation and a quasi-static magnetic field. FMR data is obtained by either sweeping the magnetic field at a constant microwave frequency, or by sweeping the frequency at a constant field. When the ferromagnetic resonance condition is achieved, it may be detected by an enhanced absorption of the microwave by the ferromagnetic sample. Thus, resonance (FMR) conditions are defined by pairs of magnetic field and microwave frequency values (H_R , f_R).

There are several ways of submitting a ferromagnetic sample to microwave excitation. Historically, FMR experimental conditions employed tubular waveguides, and samples were placed in a resonant cavity between poles of an electromagnet. More recently, new methods have been developed that are well suited to analyze film shaped samples. In particular, the wafer under test (WUT) is placed in contact with a non-magnetic waveguide transmission line (WGTL) that may be in the form of a grounded coplanar waveguide (GCPWG), coplanar waveguide (CPWG), co-axial waveguide (CWG), stripline (SL), or a microstrip (MS). The power transmitted or reflected by the WGTL is monitored as a function of the applied magnetic field and microwave frequency.

Referring to FIG. 1a, a schematic depiction is shown where output voltages are plotted as a function of a variable magnetic field at constant microwave frequency using five different values (f_1 - f_5) of microwave frequency. The center and width of the Lorentzian peaks is extracted from the data as a function of the excitation frequency. As mentioned previously, the center field is the resonance field (H_R), which is related to the excitation frequency following the Kittel formula that is rewritten in a slightly different form in equation (2) below where h is the Planck constant and μ_B is the Bohr magneton.

$$H_R(f) = [h/(\gamma \times \mu_B)] \times f - H_K \quad (\text{Eq. 2})$$

The variation of H_R with microwave frequency is shown in FIG. 1b where each of the points along curve **21** is derived from one of the Lorentzian shaped peaks H_{r1} - H_{r5} in FIG. 1a. As indicated by equation (2), the extrapolation of the data to $f = 0$ gives the value of the effective anisotropy field H_K .

The linewidth L of the resonance peak is the width at half amplitude ΔH of the resonance peak and is related to dissipative processes involved in magnetization dynamics.

The linewidth depends on the excitation frequency and the dimensionless Gilbert damping constant α according to equation (3) below where L_0 is an inhomogeneous broadening. By fitting H_R and L with respect to the excitation frequency f_R , H_K , as well as α and γ may be derived.

$$L(f) = (2h\alpha/\gamma \times \mu_B)f + L_0 \quad (\text{Eq. 3})$$

A network analyzer for detecting FMR in thin CoFe and CoFeB films on a coplanar waveguide is described by C. Bilzer et al. in "Vector network analyzer ferromagnetic resonance of thin films on coplanar waveguides: Comparison of different evaluation methods" in J. of Applied Physics 101, 074505 (2007), and in "Open-Circuit One-Port Network Analyzer Ferromagnetic Resonance" in IEEE Trans. Magn., Vol. 44, No. 11, p. 3265 (2008). In these experiments, the planar WGTL is typically attached to radiofrequency (RF) connectors by microwave electrical probes and placed between the poles of an electromagnet. Thus, given the size of the WGTL (about 5 mm long), and the size of the gap of typical electromagnets, only small size samples (normally < 1 inch in diameter) can be measured. Accordingly, wafers typically used in the microelectronics industry (having diameters of 6, 8, 12 inches or more) can only be measured with this FMR technique if they are cut into small coupons.

FIG. 2 is reproduced from "Microwave susceptibility of thin ferromagnetic films: metrology and insight into magnetization dynamics", Claus Bilzer, Ph.D. report, Universite Paris Sud – Paris XI, 2007) and depicts a conventional FMR system. Vector network analyzer **30** is connected from one port through a first coaxial cable **31** to a first microwave probe portion **32a** that is attached to coplanar waveguide (CPWG) **36**. A top surface of the CPWG adjoins a magnetic film **34** mounted on a substrate. When a microwave frequency from probe **32a** and an external magnetic field **33** are applied in an x-axis direction across the magnetic film, an output signal in a transmission mode passes into a second microwave probe portion **32b** and then through a second coaxial cable **35** before returning to the VTA at a second port. Magnetic film size **b** is typically

restricted to 1 inch or less, which means the magnetic film sample **34**, must be cut from a whole wafer.

Since conventional FMR techniques are destructive, impractical, and time consuming, they are undesirable to an extent that prevents wide acceptance of FMR as a characterization tool in the magnetic data storage industry. An improved FMR measurement system and technique is needed that enables fully automated FMR measurements on whole wafers for faster throughput, and results in reduced cost by providing a non-invasive test that avoids cutting wafers.

SUMMARY

One objective of the present disclosure is to provide a fully automated system for FMR measurements so that wafer throughput is improved, and wafer destruction associated with wafer cutting to prepare test samples is avoided.

A second objective of the present disclosure is to provide a fully automated system according to the first objective that includes a waveguide transmission line (WGTL) for performing the FMR test with the capability to characterize a plurality of sites on magnetic thin films and multilayers formed on unpatterned or patterned whole wafers.

These objectives are achieved according to one embodiment of the present disclosure with a FMR test system that is configured around a controller (computer) linked to an electrical probe station comprising a WGTL connected on one end to a RF generator and on the other end to a RF power detector (diode), a magnetic field pole positioned above the WGTL, and a wafer chuck that holds a wafer under test (WUT) under the WGTL and moves laterally in a preprogrammed direction with respect to the WGTL. A RF input cable from the RF generator is attached to a first end launch RF connector, which is connected to a first end of the WGTL and provides a RF input signal thereto. The WGTL is connected at a second end to a second end launch RF connector that is attached to a RF output cable. Both end launch RF connectors are rigidly clamped to a mounting plate, and at least a portion of the WGTL protrudes through and below an opening in the mounting plate.

According to one FMR measurement mode disclosed herein, the controller directs the wafer chuck and WUT to move in an x-axis and/or y-axis direction parallel to the plane of the mounting plate such that the WGTL is aligned above a predetermined (x, y) coordinate on the WUT. The WGTL is separated from the WUT by a gap distance in the z-axis direction thereby avoiding contact. Then, the WUT is moved in a vertical direction to establish contact between a WGTL bottom surface and a top surface of a magnetic film on the WUT. In other embodiments, the WUT is held stationary while the mounting plate and WGTL are moved above a series of predetermined (x, y) coordinates on the WUT. At certain x-axis and y-axis coordinates that are pre-programmed into the controller, the WGTL is vertically moved to contact the magnetic film top surface. In some embodiments, the WGTL has a substantially U-shape while in other embodiments, the WGTL has planar top and bottom surfaces.

While the WGTL makes contact with a portion of the magnetic film top surface, a static magnetic field is applied from a magnetic pole piece that is positioned above the opening in the mounting plate and directly above the WGTL contact area. The WGTL transmits a sequence of microwave frequencies (RF input signals) to the wafer. A FMR condition is established in the magnetic film with each applied microwave frequency, and the extent of microwave absorption by the magnetic film is dependent on the magnitudes of the microwave frequency, static magnetic field, and magnetic properties of the thin magnetic film.

As a result of FMR absorption by the magnetic film, there is a power loss between the first and second ends of the WGTL that is detected by the RF power diode. The RF power diode also known as the RF detector converts each RF output signal from the WGTL to a voltage readout that the controller uses to calculate H_k , and α , for example, for the magnetic film. After each FMR measurement, the wafer chuck and WUT are lowered to a gap distance $k > 0$, and then moved to the next (x, y) coordinate for a subsequent FMR measurement. Thus, the FMR measurement sequence comprises a "step and repeat" pattern in which the chuck and WUT are moved laterally (stepped) to align the WGTL above a new (x, y) coordinate on the WUT, raised to make contact with the WGTL, and then lowered to the gap distance after the

measurement. The area of the contacted region on the magnetic film is sufficiently large to detect H_k and α for a plurality of thousands of magnetic storage devices within the contacted region.

According to one embodiment, a commercial WGTl with a flat, rectangular shape is modified to provide sufficient flexibility that enables the WGTl to be bent without breakage.

The present disclosure also encompasses an embodiment where the RF input and output cables are attached to first and second end launch RF connectors, respectively, which in turn are affixed to a top surface of a flat WGTl. The WGTl bottom surface is below the mounting plate and is unencumbered when contacting a magnetic film top surface during a FMR measurement. Preferably, the end launch RF connectors should not extend below the plane of contact between the WGTl and magnetic film to allow contact or close proximity between the WGTl and WUT.

Since a single controller may be employed to manage all aspects of the testing including wafer chuck and mounting plate movement, RF signal processing, magnetic field generation, and compilation of the test data, throughput is optimized so that the system and FMR measurement method may be readily implemented in an engineering or production environment.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1a shows a schematic description of the typical series of Lorentzian shaped peaks derived from ferromagnetic resonance measurements taken for 24 GHz to 48 GHz microwave frequencies.

FIG. 1b shows a plot of resonance field (H_R) as a function of the microwave frequencies used in FIG. 1a.

FIG. 2 is a diagram that illustrates a prior art FMR measurement scheme.

FIG. 3 is a diagram showing the various components of a fully automated FMR measurement system according to a first embodiment of the present disclosure that represents a transmission mode for performing FMR measurements.

FIG. 4 is a diagram showing the various components of a fully automated FMR measurement system according to a second embodiment of the present disclosure that represents a reflective mode for performing FMR measurements.

FIG. 5 is cross-sectional view of a FMR measurement system according to the present disclosure wherein a bent WGTL is attached to a mounting plate, and the wafer under test is held on a movable chuck during FMR measurements.

FIG. 6 is an oblique view of the embodiment in FIG. 5 where the bent WGTL is suspended over an opening in a mounting plate, and a middle portion of the WGTL is below the plane of the mounting plate.

FIG. 7a and FIG. 7b are a top view, and cross-sectional view, respectively, of a flat WGTL with backside end launch RF connector attachments according to another embodiment of the present disclosure.

FIG. 8 is a flow diagram showing various steps of performing a FMR measurement according to a method of the present disclosure.

FIG. 9 shows the FMR measurement results of H_K as a function of x-axis and y-axis coordinates of a perpendicular magnetic tunnel junction (pMTJ) stack with a nominal uniform thickness across the entire wafer, and obtained according to a method described herein.

FIG. 10 illustrates FMR measurement results for damping parameter α as a function of x-axis and y-axis coordinates of a pMTJ stack with a nominal uniform thickness across the entire wafer, and obtained according to a method of the present disclosure.

FIG. 11a depicts the FMR measurement results of H_K as a function of x-axis and y-axis coordinates for a magnetic thin film with a variable thickness on a wafer according to an embodiment of the present disclosure.

FIG. 11b is a plot of H_K vs. thickness taken from data obtained during the FMR measurements used to generate FIG. 11a.

DETAILED DESCRIPTION

The present disclosure is a scanning FMR system that is designed to measure magnetic properties including H_K and α for magnetic films or multilayers on a whole wafer at a plurality of locations identified by their (x, y) coordinates. The scanning FMR system is fully automated and features a mounting plate with a center opening in which a waveguide transmission line (WGTL) is suspended from two ends that are attached to RF connectors rigidly held on a mounting plate. It should be understood that the term “RF connector” encompasses various types of RF connectors including end launch RF connectors mentioned in the exemplary embodiments. However, other embodiments may comprise other types of RF connectors used in the art but not described herein. X-axis and y-axis coordinates on the wafer under test (WUT) are in a plane that is aligned parallel to and below the plane of the mounting plate. Each FMR measurement site on a magnetic film has a pair of coordinates (x_n, y_n) where n is an integer. The z-axis direction in the drawings is orthogonal to the plane of the WUT. The present disclosure also encompasses a FMR test method for measuring magnetic properties of one or more films on patterned or unpatterned wafers.

Referring to FIG. 3, one embodiment of a FMR measurement system according to the present disclosure is depicted in a diagram that shows the layout of the major components. There is a computer hereafter called the controller **40** to manage the movement of the WGTL **45** and the mounting plate **46** to which the WGTL is affixed. The magnetic field pole **83** may also be moved by the controller to maintain a position above the WGTL and the test location of a magnetic film **43f** on the WUT **43** as explained later. It should be understood that the term “magnetic film” may comprise one or a plurality of magnetic films formed in a stack of layers. In some embodiments, the WUT is held on a top surface of a wafer chuck **42** by a vacuum, and the wafer chuck and WUT are moved in a programmed manner while the magnetic field pole, WGTL, and mounting plate are maintained in a stationary position. In preferred embodiments, a magnetic field is applied to a predetermined (x_n, y_n) coordinate

on the WUT while a signal path layer of the WGTl contacts a top surface **43t** of the magnetic film at the (x_n, y_n) coordinate. As a result of simultaneously applying a microwave frequency by the WGTl and magnetic field of up to 3 Tesla from the magnetic pole piece, a ferromagnetic resonance (FMR) condition is established in the magnetic film proximate to the predetermined (x, y) coordinate on the WUT. The WGTl may be a microstrip, grounded coplanar waveguide, coplanar waveguide, stripline, or coaxial waveguide.

The RF detector may be a power diode **55** that detects a RF output signal from the WGTl corresponding to a RF power loss caused by the FMR condition where a certain amount of microwave power is absorbed and excites the magnetic film to a resonance state. After the FMR measurement is performed at the (x_n, y_n) coordinate, the wafer chuck and WUT are lowered **50d** via a signal through link **41c** to reestablish a gap below the WGTl. Subsequently, the wafer chuck and WUT are moved to another predetermined (x_n, y_n) coordinate and the chuck is raised **50u** to enable the WGTl to contact magnetic film top surface **43t** for another FMR measurement.

The controller **40** has a first link **41a** to a power generator **47** that is responsible for providing an appropriate magnetic field from the magnetic field pole **83** so that an applied microwave frequency and the applied field induce a FMR condition in the magnetic film **43f** when the probe chuck **42** and WUT **43** are raised **50u** to enable contact of the magnetic film with a WGTl bottom surface (not shown) that is suspended through and below an opening in the mounting plate **46**. Meanwhile, the controller has a second link **41b** to a RF generator **49** that provides a plurality of microwave frequencies through RF input cable **51a** to one end of the WGTl.

In a preferred operating mode, the applied magnetic field is varied (swept from a minimum to a maximum value) at constant microwave frequency. The FMR measurement may be repeated for a plurality of different microwave frequencies. The RF power diode converts the power output to a voltage signal that is transmitted through an output cable **51b** to the controller. Thereafter, the controller calculates H_k and α based on each pair of applied magnetic field value and applied microwave frequency used to establish a FMR condition, and

on voltage output data from the RF power diode for each (x_n, y_n) coordinate used in the FMR measurement sequence.

The present disclosure anticipates that layouts other than the one illustrated in FIG. 3 may be employed to generate the microwave excitation (FMR condition) of a magnetic film sample, and detect the absorption therein. For instance, a vector network analyzer (VNA) similar to the VNA **30** depicted in FIG. 2 may be used as a RF output generator and RF input analyzer. In another embodiment related to pulsed inductive microwave magnetometry (PIMM), a pulse generator and a time-resolved oscilloscope may serve as a RF source and RF analyzer, respectively. In yet another embodiment, a lock-in amplifier detection technique known to those skilled in the art may be employed to amplify the FMR output signal (power loss).

According to various embodiments of the present disclosure, FMR measurements are performed by analyzing a RF signal transmitted through a WGTl as described with respect to FIG. 3 and FIGS. 5-6, or by measuring a RF signal that is reflected from a waveguide terminated by an open-circuit or short-circuit. An embodiment showing a reflectance mode of operation is depicted in FIG. 4 where a directional coupler **75** is inserted between the RF generator **49** and WGTl **45** to transmit a RF input signal to the WGTl and receive a RF output signal reflected from the WGTl. Alternatively, a power divider or a bias tee may be used instead of the directional coupler as appreciated by those skilled in the art. Microwave frequencies are inputted from the RF generator through a first input cable **51a1** to the directional coupler and then through a second input cable **51a2** to the WGTl. All other components of the transmission mode layout in FIG. 3 are retained.

In some embodiments, the RF input and output signals pass through an end launch RF connector (not shown) positioned between the second input cable and the WGTl. In particular, the directional coupler receives reflected RF signals (output signals) from the WGTl through cable **51a2** and then directs the signals to the RF power diode **55** where a conversion occurs to a voltage output signal for each pair of applied magnetic field and applied microwave frequency (H_R, f_R) as previously described. The output signal is then transmitted to the controller **40** through output cable **51b**.

Referring to FIG. 5, a cross-sectional view of a FMR measurement system based on RF signal transmission through a WGTL is shown according to a first embodiment of the present disclosure, and includes the magnetic pole piece **83**, bent WGTL **45**, and magnetic film **43f** on WUT **43**. In the exemplary embodiment, the WGTL has a first end attached to an end launch RF input connector **54a** and a second end connected to an end launch RF output connector **54b** such that both end launch RF input/output connectors are above a top surface **46t** of mounting plate **46**. The WGTL is bent in a substantially U-shape and protrudes through opening **46a** such that a middle portion **45b** hereafter called the tip portion is below a bottom surface **46b** of the mounting plate. According to one embodiment, the mounting plate along with the WGTL and WUT are installed on a commercial electrical probe station that is available from different vendors.

During intervals when no FMR measurements are being performed, the tip portion **45b** is a gap distance $k > 0$ from the top surface **43t** of magnetic film **43f** on WUT **43**. As indicated previously, when the FMR system is programmed to perform a FMR measurement at a certain (x_n, y_n) coordinate, the wafer chuck is raised so that $k = 0$ until the FMR measurement is completed. In an alternative embodiment, k is proximate to 0 and sufficiently small, preferably less than 100 micrometers, to enable efficient transmission of microwaves from the WGTL to the magnetic film. It is important that the magnetic pole tip **83b** is above opening **46a** and aligned over the (x_n, y_n) coordinate where tip portion **45b** makes contact with top surface **43t** so that the same region proximate to the (x_n, y_n) coordinate is exposed to both of the magnetic field and microwave frequency.

Referring to FIG. 6, an oblique view of the mounting plate **46** and WGTL **45** in FIG. 5 is depicted with the magnetic pole piece removed. According to one embodiment, opening **46a** has two parallel sides **46d** that are aligned in an x-axis direction and may be substantially orthogonal to mounting plate sides **46s1**, **46s2**. At each end of opening **46a** where sides **46d** terminate, there is an end launch RF connector. One “outer” end **54a1** of a first end launch RF connector is attached to RF input connector **52a** and a second “inner” end **54a2** is connected to end **45e** of the WGTL. Meanwhile, an inner end **54b2** of a second end launch RF connector is attached to end **45f** of the WGTL, and an

outer end **54b1** thereof is attached to RF output connector **52b**. Thus, microwave frequencies in the range of 1-100 GHz are sent from the RF generator (not shown) through input cable **51a** to the WGTL via the first end launch RF connector, and output RF signals are transmitted via the second end launch RF connector to RF diode **55**. According to one embodiment, WGTL **45** is bent in order to be compatible with suspension through opening **46a** in the mounting plate design, and to provide a small contact area (plurality of square millimeters) with the magnetic film on the underlying WUT.

The entire WGTL assembly (WGTL and end launch RF connectors) is affixed to the mounting plate **46** by two removable and retractile clamps **56**. Opening **46a** may be formed therein by a conventional method and has an x-axis dimension of sufficient length to enable a bent WGTL to be suspended between the two clamps, and have a middle tip portion below the plane of the mounting plate.

The present disclosure also encompasses a second embodiment of an FMR measurement system similar to the scheme depicted in FIG. 6 except the WGTL is not bent and has planar top and bottom surfaces. To enable a bottom surface of a flat WGTL to make contact with a magnetic film beneath opening **46a** in the mounting plate, a different end launch RF connector is required.

Referring to the top view of the second embodiment in FIG. 7a, a key feature in addition to the flat WGTL **45'** is a second type of end launch connector **54c**, **54d** which is affixed to a top surface of a rigid substrate **63** proximate to ends **45e'**, **45f'**, respectively, of the flat WGTL by bolts **58**. A RF input cable (not shown) is connected to the RF connector **52f** of the end launch connector **54c** proximate to end **45e'**, and a RF power diode (not shown) is connected to the RF connector **52f** of the end launch connector **54d** proximate to end **45f'**. Each end launch connector has a pin **54p** at an inner side that contacts a top conductor layer **61t**. The bolts preferably extend through an opening (not shown) into the rigid substrate to securely hold the WGTL, especially during lateral movements in the (x, y) plane and vertical movements in a z-axis direction that are required for FMR measurements. Plane **70-70** is aligned along the x-axis direction and bisects the flat WGTL.

FIG. 7b depicts a cross-sectional view of the flat WGTL **45'** and end launch connectors at plane **70-70** in FIG. 7a. As a result of affixing the end launch

connectors **54c** and **54d** to a top surface **63t** of the rigid substrate that is an upper layer in the WGTL, the bottom surface that comprises signal path layer **61b** is clear to make contact with an underlying magnetic film **43f** during a FMR measurement. According to one embodiment, at least a bottom portion of the flat WGTL including the signal path layer is suspended through an opening in the mounting plate. Alternatively, the flat WGTL may be suspended below the opening. Dielectric layer **60b** separates the signal path layer from rigid substrate **63** and top ground path layer **62a**. Gap **k** is shown during a stationary position between FMR measurements when there is no contact between the WGTL and magnetic film. Top conductor layer **61t** is connected to the signal path layer by a first via **61v1** that may be positioned below a first pin **54p** at end launch connector **54c**, and by a second via **61v2** that may be positioned below the second pin **54p** at end launch connector **54d**. Ground path and signal path layers are typically made of a conductive metal.

During a FMR measurement when a magnetic field is applied to an area around an (x, y) coordinate of the magnetic film contacted by the WGTL, a microwave frequency passes through end launch connector **54c** and the top conductor layer **61t**, and then through via **61v1** and into the signal path layer **61b**. A portion of the microwave power is absorbed by the magnetic film **43f** during a FMR condition so that the output RF signal carried through via **61v2** and out through end launch connector **54d** has reduced power compared with the input RF signal. The RF power diode (not shown) converts the output RF power signal for each (H_R , f_R) pair to a voltage measurement that is relayed to the controller.

Referring to FIG. 8, a FMR measurement method is illustrated in a flow diagram according an embodiment of the present disclosure, and may be employed for both of the embodiments relating to a bent WGTL or flat WGTL. In step **110**, the controller (described earlier with regard to a transmission mode in FIG. 3 or a reflectance mode in FIG. 4) commands a WGTL through link **41c**, for example, to contact a first location that is represented by a (x, y) coordinate on a magnetic film to be tested. Contact is achieved by lowering the WGTL and mounting plate, or by raising the wafer chuck and overlying wafer under test with an exposed top surface of the magnetic film (see movement **50u** in FIGS. 3, 4). Next, in step **111**, the controller through another link **41b** instructs a RF

generator to send a microwave frequency F1 to the WGTL while an overlying magnetic pole piece applies a magnetic field at the selected (x, y) coordinate.

As a result of the simultaneous application of microwave frequency F1 and the magnetic field, the magnetic film achieves a FMR condition and absorbs a portion of the microwave power that depends on the magnetic properties of the magnetic film, F1, and the applied field (H_R). Accordingly, in step **112**, the RF power diode detects a reduced power value in the RF output signal compared with the value specified by the controller in the RF input signal from step **111**.

In step **113**, the RF power diode converts the RF output signal to a voltage measurement that is transmitted to the controller and indicates the microwave absorbance by the magnetic film for applied microwave frequency F1 and applied magnetic field H_R .

Step **114** comprises a repetition of steps **111-113** except the RF input signal has a second frequency F2 that is applied to the magnetic film at the previously selected (x, y) coordinate after F1 is applied. In some embodiments, steps **111-113** are repeated a plurality of times at each (x, y) coordinate used for the FMR measurement method. In other words, a third frequency F3 that differs from F1 and F2 may be applied during an interval of time after F2, and so forth up to an "nth" frequency F_n after F3 is applied. Note that the applied magnetic field is swept between a minimum and a maximum value when each frequency F1 up to F_n is applied according to a preferred embodiment. Thus, a FMR condition occurs with each applied frequency, and each FMR condition has a unique microwave absorbance that is translated into a corresponding voltage signal by the RF power diode. In an alternative embodiment, the applied magnetic field is held constant while the microwave frequencies are varied (swept) from F1 up to F_n to establish a FMR condition.

Referring to step **115**, the controller commands the wafer chuck and overlying magnetic film to be lowered (movement **50d** in FIG. 3) thereby disengaging the WGTL from making contact with the first location. Then, in an embodiment where the wafer chuck and wafer make all the movements in the x-axis and y-axis directions, the controller directs the wafer chuck to move to a second location where the WGTL tip portion is aligned above a different (x, y) coordinate from the initial (x, y) coordinate. The wafer chuck and the magnetic film on the WUT are raised to again make contact with the WGTL.

Thereafter, steps **111-114** are repeated to complete a FMR measurement at the second location. Note that each location may comprise a contact area of a plurality of square millimeters, and each (x, y) coordinate may be a center point in the area contacted by the WGTL.

Depending on the size of the magnetic film area to be contacted by the WGTL, and the number of different positions desired for an FMR measurement, step **116** indicates that steps **111-115** may be repeated a plurality of times to yield a plurality of FMR measurements involving “m” different (x, y) coordinates each with a plurality of (H_R , f_R) pairs where f_R is one of F_1 up to F_n . At step **117**, a decision is made whether or not all of the pre-selected (x, y) coordinates on the magnetic film have been tested. If “no”, another FMR measurement is taken at a different (x, y) coordinate. If “yes”, step **118** indicates the FMR measurement process is complete.

As mentioned earlier, the controller is capable of determining magnetic properties in the magnetic film at each location corresponding to a different (x, y) coordinate. Each FMR measurement yields one or more pairs (frequency, field) also referred to as (H_R , f_R) pairs in equation (1) corresponding to each FMR condition. The controller uses FMR measurement data and one or more of equations (1) – (3) described previously to determine H_k , α , and in some cases γ and inhomogeneous broadening (L_0).

An experiment was performed using the FMR system with a bent WGTL shown in FIGS. 5-6 and demonstrates how effective perpendicular magnetic anisotropy field (H_k) is monitored across an unpatterned film comprised of a stack of magnetic tunnel junction (MTJ) layers. In this example, 43 regions each having a different (x, y) coordinate on an uncut 8-inch diameter wafer were tested by applying microwave frequencies between 10 - 40 GHz and magnetic fields up to 1 Tesla (10000 Oe) according to a FMR measurement method of the present disclosure. Each region has a rectangular shape with a length of about 10 mm along the x-axis direction, and a width of about 9 mm in the y-axis direction. The FMR measurement at each (x, y) coordinate required about two minutes of process time for a total FMR measurement time of around 90 minutes for the entire wafer.

FIG. 9 shows a map of the H_K results and FIG. 10 illustrates a map of the damping coefficient α result for each of the 43 regions on the 8-inch wafer as a function of their x-axis and y-axis coordinates. H_K varies from 9760 Oe in the upper left to 9670 Oe in the lower right corner of the wafer. The MTJ stack used for this experiment was a CoFeB/MgO/CoFeB based MTJ structure. Results show that the MTJ stack has a very high perpendicular magnetic anisotropy (PMA), and a substantially uniform thickness across the wafer.

In a second experiment, the same MTJ stack of layers was retained from the first experiment. However, the free layer thickness was purposely varied from 17 Angstroms in the upper left portion of the wafer by small increments to 18.5 Angstroms in the lower right corner to demonstrate how the FMR measurement system and method of the present disclosure may be advantageously used as a tool to explore H_K dependence on free layer thickness. The experimental results are mapped in FIG. 11a and show how H_K varies from 10500 Oe in the upper left portion of the wafer to 8760 Oe in the lower right corner of the wafer. FIG. 11b shows the results of H_K as a function of thickness along the plane **95-95** in FIG. 11a. In particular, a substantially linear plot is formed which indicates H_K steadily increases as the free layer thickness is gradually reduced from 18.5 Angstroms to 17 Angstroms.

RF connectors, the probe station (platform), RF generator, RF power diode, input and output cables, as well as alternative RF devices such as vector network analyzers, pulse generators, and time-resolved oscilloscopes are commercially available. A suitable magnet comprising a magnetic pole piece that delivers the required magnetic field to induce a magnetic resonance according to the present disclosure is also commercially available or may be custom built by one skilled in the art.

While this disclosure has been particularly shown and described with reference to, the preferred embodiment thereof, it will be understood by those skilled in the art that various changes in form and details may be made without departing from the spirit and scope of this disclosure.

We claim:

1. A ferromagnetic resonance (FMR) measurement system for a wafer under test (WUT) on which one or a plurality of magnetic films are formed, comprising:
 - (a) a waveguide transmission line (WGTL) connected to a generator of microwaves;
 - (b) a magnet that provides a magnetic field which together with a simultaneous application of a microwave frequency is configured to induce a magnetic resonance condition in the one or plurality of magnetic films; and
 - (c) a system for detecting microwave absorbance by the one or plurality of magnetic films when a magnetic resonance condition is establishedwherein the WGTL and WUT are configured to move laterally and vertically relative to one another such that the WGTL contacts, or is placed proximate to the WUT at predetermined positions.
2. The FMR measurement system of claim 1 wherein the WGTL and WUT are installed in an electrical probe station.
3. The FMR measurement system of claim 1 wherein the WGTL is moved with respect to the WUT and the one or plurality of magnetic films, which are held stationary.
4. The FMR measurement system of claim 1 wherein the WUT and the one or plurality of magnetic films are moved with respect to the WGTL, which is held stationary.
5. The FMR measurement system of claim 1 wherein the WGTL is placed proximate to the WUT such that the vertical distance between the WGTL and WUT is less than 100 micrometers during a FMR measurement.
6. The FMR measurement system of claim 1 wherein the WGTL is a microstrip.
7. The FMR measurement system of claim 1 wherein the WGTL is a coplanar waveguide or a grounded coplanar waveguide.
8. The FMR measurement system of claim 1 wherein the WGTL is a stripline.
9. The FMR measurement system of claim 1 wherein the WGTL is a coaxial waveguide.

10. A scanning ferromagnetic resonance (FMR) measurement system, comprising:

(a) a controller with a first link to a RF generator, a second link to a power generator that is connected to a magnet, and a third link to one or both of a mounting plate on which a bent waveguide transmission line (WGTL) is mounted, and a wafer chuck configured to hold an overlying whole wafer under test (WUT) having a magnetic film with an exposed upper surface, the mounting plate and/or wafer chuck are programmed to move laterally and vertically in a step and repeat fashion;

(b) the RF generator that is configured to provide a sequence of RF input signals each comprising a different microwave frequency through a RF input cable to the bent WGTL;

(c) the bent WGTL that has a middle tip portion which is configured to contact a predetermined region of the exposed upper surface of the magnetic film during a FMR measurement to sequentially transmit the different microwave frequencies thereto; and

(d) the magnet having a magnetic pole piece aligned above the bent WGTL middle tip portion and providing a magnetic field through a mounting plate opening on the predetermined region of the magnetic film such that a FMR condition is established in the predetermined region thereby causing a unique microwave absorbance for each different microwave frequency (f_R) that results in a RF power loss for each combination of H_R and f_R and is detected from a RF output signal that passes from the WGTL to a RF detector, the RF detector is configured to send a voltage signal as an FMR measurement to the controller such that one or more magnetic properties are determined for the magnetic film.

11. The scanning FMR measurement system of claim **10** wherein the bent WGTL and mounting plate are installed in an electrical probe station.

12. The scanning FMR measurement system of claim **10** further comprised of a first RF connector that connects the RF input cable to the bent WGTL, and a second RF connector that connects the bent WGTL to the RF detector, and wherein the first and second RF connectors do not contact the exposed top surface of the magnetic film or extend beyond a plane of contact between the bent WGTL and the magnetic film.

13. The scanning FMR measurement system of claim **12** comprising a transmission mode for performing the FMR measurement wherein the RF input signal is transmitted through the first RF connector and the RF output signal is transmitted through the second RF connector.

14. The scanning FMR measurement system of claim **12** wherein the first and second RF connectors are end launch RF connectors.

15. The scanning FMR measurement system of claim **10** further comprised of a directional coupler, power divider, or bias tee that receives the RF input signal from the RF generator and then transmits the RF input signal through the RF input cable to the WGTL, the directional coupler, power divider, or bias tee also receives a reflected RF output signal from the WGTL and transmits the reflected RF output signal to the RF detector in a reflectance mode for performing the FMR measurement.

16. The scanning FMR measurement system of claim **10** wherein the bent WGTL has a substantially U-shape.

17. The scanning FMR measurement system of claim **10** wherein the mounting plate and bent WGTL are moved with respect to the WUT and magnetic film, which are held stationary.

18. The scanning FMR measurement system of claim **10** wherein the WUT and magnetic film are moved with respect to the WGTL and mounting plate, which are held stationary.

19. The scanning FMR measurement system of claim **10** wherein the bent WGTL and magnetic film are separated after the FMR measurement by a vertical movement to establish a gap therebetween before a lateral movement is performed to align the bent WGTL over another predetermined region in the magnetic film.

20. The scanning FMR measurement system of claim **10** wherein the FMR condition is established with each of the different microwave frequencies by sweeping the magnetic field from a minimum value to a maximum value.

21. The scanning FMR measurement system of claim **10** wherein the FMR condition is established by holding the magnetic field constant and sweeping with a plurality of different microwave frequencies applied in a sequential order.

22. A scanning ferromagnetic resonance (FMR) measurement system, comprising:

(a) a controller with a first link to a RF generator, a second link to power generator that is connected to a magnet, and a third link to one or both of a mounting plate to which a flat waveguide transmission line (WGTL) is attached, and a wafer chuck configured to hold an overlying whole wafer under test (WUT) having a magnetic film with an exposed upper surface, the mounting plate or wafer chuck are programmed to move laterally and vertically in a step and repeat fashion;

(b) the RF generator configured to provide a sequence of RF input signals each comprising a different microwave frequency through a RF input cable to the flat WGTL;

(c) the flat WGTL that is attached to the mounting plate through a first RF connector that is affixed to a top surface of the WGTL proximate to a first end thereof, and through a second RF connector affixed to a top surface of the WGTL proximate to a second end thereof, the flat WGTL has a bottom surface below a mounting plate opening and is configured to contact a predetermined region on the exposed upper surface of the magnetic film, and to sequentially transmit the plurality of microwave frequencies thereto; and

(d) the magnet having a magnetic pole piece aligned above the flat WGTL and providing a magnetic field through the mounting plate opening on the predetermined region of the magnetic film such that a FMR condition is established in the predetermined region thereby causing a unique microwave absorbance for each frequency (f_R) that results in a RF power loss for each combination of H_R and f_R and is detected from a RF output signal that passes from the WGTL to a RF power diode, the RF power diode is configured to convert the output signal to a voltage signal and to send the voltage signal to the controller such that one or more magnetic properties are determined for the magnetic film.

23. The scanning FMR measurement system of claim **22** wherein the flat WGTL and mounting plate are installed in an electrical probe station.

24. The scanning FMR measurement system of claim **22** wherein the vertical movement of the mounting plate or wafer chuck causes the bottom surface of the flat WGTL to contact the predetermined region of the exposed upper surface of the magnetic film.

25. The scanning FMR measurement system of claim **22** wherein the first and second RF connectors do not contact the exposed top surface of the magnetic film or extend below a plane of contact between the flat WGTL and exposed upper surface of the magnetic film.

26. The scanning FMR measurement system of claim **22** wherein the mounting plate and flat WGTL are moved with respect to the WUT and magnetic film, which are held stationary.

27. The scanning FMR measurement system of claim **22** wherein the WUT and magnetic film are moved with respect to the flat WGTL and mounting plate, which are held stationary.

28. The scanning FMR measurement system of claim **22** wherein the flat WGTL and magnetic film are separated after the FMR measurement by a vertical movement to establish a gap therebetween before a lateral movement is performed to align the flat WGTL over another predetermined region in the magnetic film.

29. The scanning FMR measurement system of claim **22** wherein the flat WGTL is comprised of a top conductor layer, a rigid substrate layer, a bottom ground plane layer including a signal layer, and a dielectric layer between the rigid substrate layer and bottom ground plane layer.

30. The scanning FMR measurement system of claim **22** wherein the FMR measurement is performed with a transmission mode wherein the RF input signal passes through the first RF connector, and the RF output signal passes through the second RF connector.

31. The scanning FMR measurement system of claim **22** further comprised of a directional coupler, power divider, or bias tee that receives the RF input signal from the RF generator and then transmits the RF input signal through the RF input cable to the WGTL, the directional coupler, power divider, or bias tee also receives a reflected RF output signal from the WGTL through the RF input cable, and transmits the reflected RF output signal to the RF detector in a reflectance mode for performing the FMR measurement.

32. The scanning FMR measurement system of claim **22** wherein the first and second RF connectors are end launch connectors.

33. A method of performing a scanning ferromagnetic resonance (FMR) measurement on a whole wafer under test (WUT) having an exposed magnetic film thereon, comprising:

(a) providing a wafer chuck on which the WUT is held, and having a first link to a controller;

(b) providing a waveguide transmission line (WGTL) that is configured to contact or be placed proximate to a first location on the exposed magnetic film;

(c) applying a sequence of RF input signals from a RF generator that has a second link to the controller, each RF input signal passes through the WGTL and comprises a different microwave frequency that is sequentially transmitted to the first location;

(d) applying a magnetic field from an overlying magnetic pole piece simultaneously with each different microwave frequency to establish a FMR condition thereby resulting in a RF output signal for each pair of an applied microwave frequency value and an applied magnetic field value; and

(e) transmitting a sequence of output RF signals from the WGTL to a RF detector that is configured to convert each output RF signal to a voltage signal and to send each voltage signal to the controller, the controller determines one or more properties in the exposed magnetic film.

34. The method of claim **33** wherein the WGTL and mounting plate are installed in an electrical probe station.

35. The method of claim **33** wherein contact between the WGTL and the exposed magnetic film is achieved by a vertical movement of the mounting plate or a vertical movement of the wafer chuck.

36. The method of claim **33** wherein the WGTL is affixed at two ends to a mounting plate, and is suspended through or below a mounting plate opening in order to contact or be placed proximate to the exposed magnetic film.

37. The method of claim **33** further comprised of performing a second FMR measurement at a second location on the exposed magnetic film after completing steps (a)-(e).

38. The method of claim **37** wherein performing the second FMR measurement comprises:

- (a) separating the WGTL and exposed magnetic film using a vertical movement of the mounting plate or wafer chuck;
 - (b) performing a lateral movement of the mounting plate or wafer chuck such that the WGTL and magnetic pole piece are aligned above the second location; and
 - (c) performing a vertical movement of the mounting plate or wafer chuck such that the WGTL contacts or is moved proximate to the exposed magnetic film.
39. The method of claim **33** wherein the different microwave frequencies are between 1 and 100 GHz.
40. The method of claim **33** wherein the magnitude of the magnetic field is up to 3 Tesla.

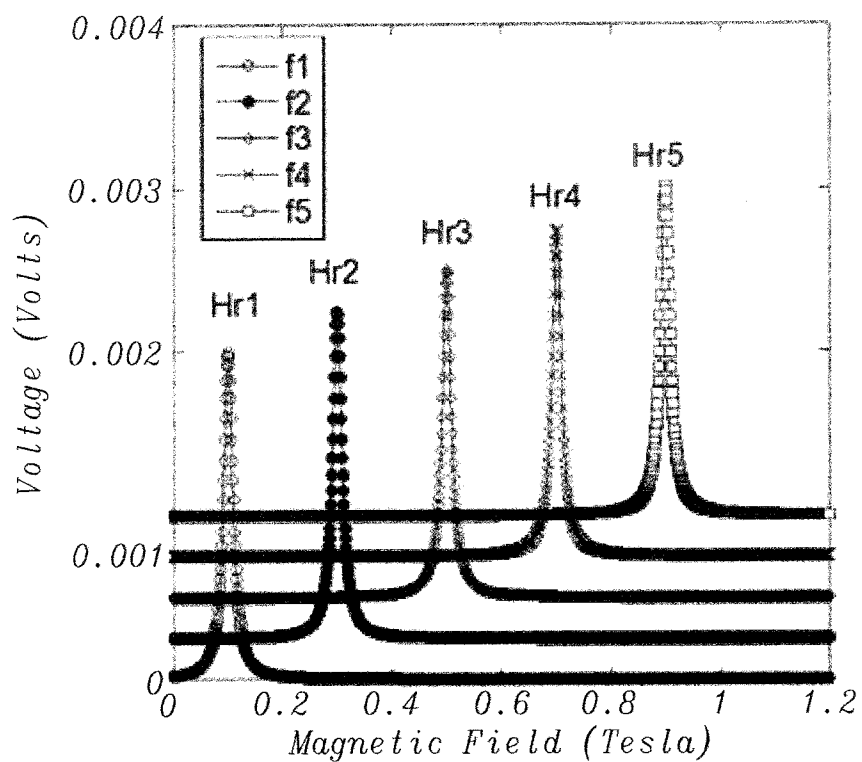


FIG. 1a Prior Art

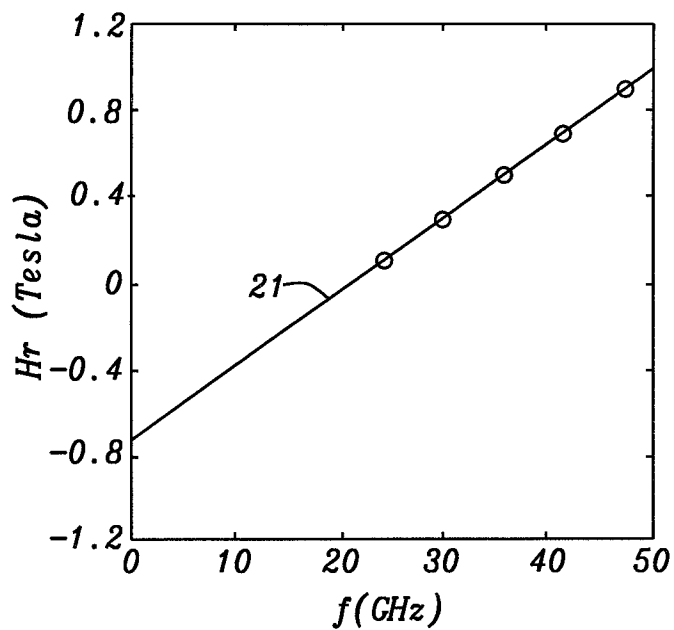


FIG. 1b Prior Art

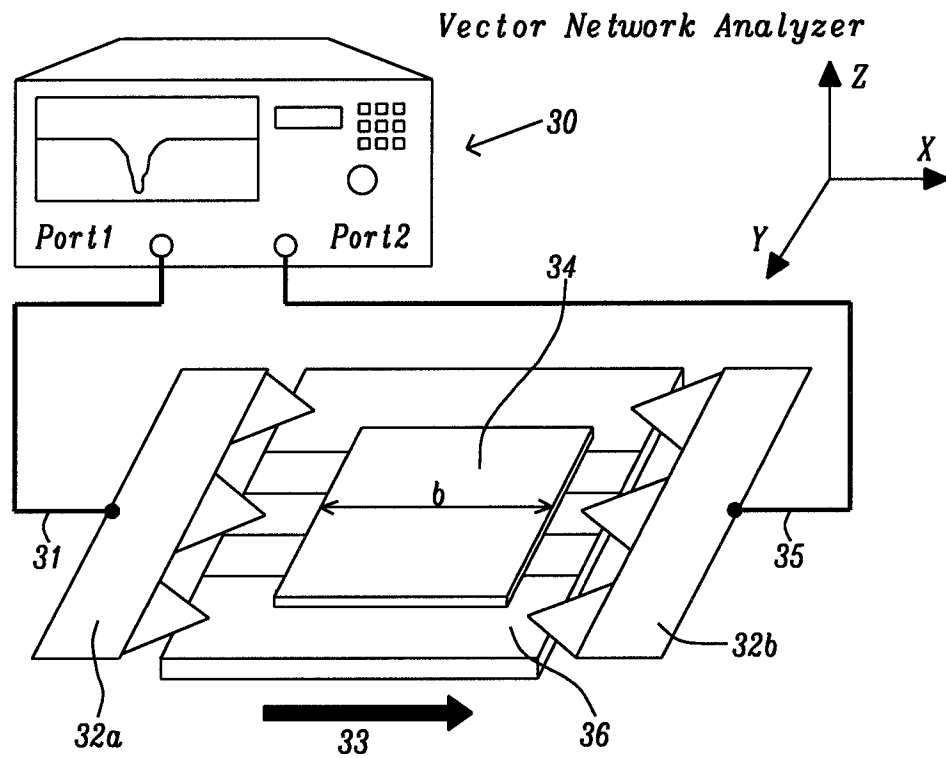


FIG. 2 Prior Art

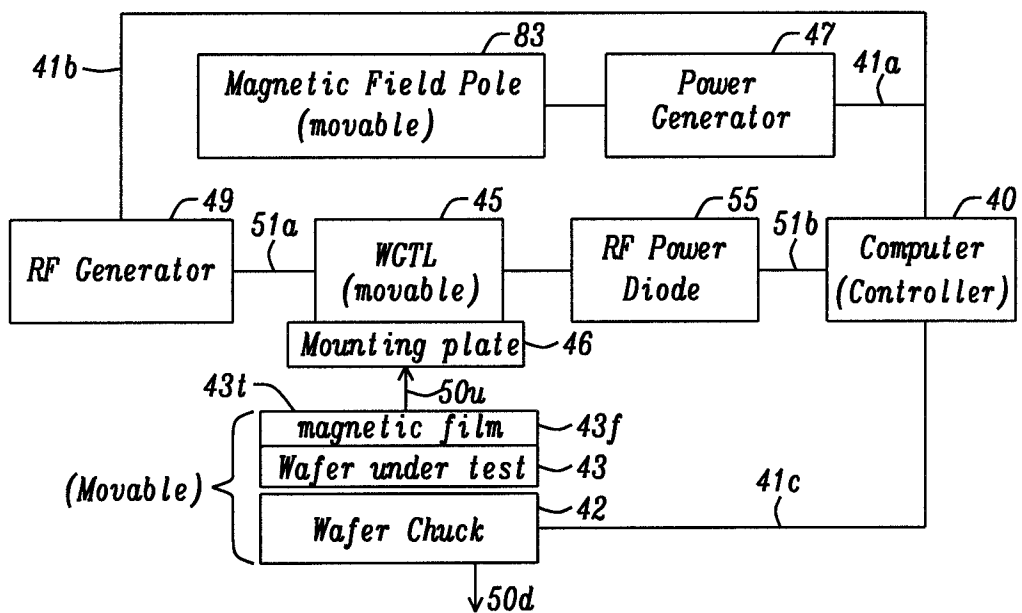


FIG. 3

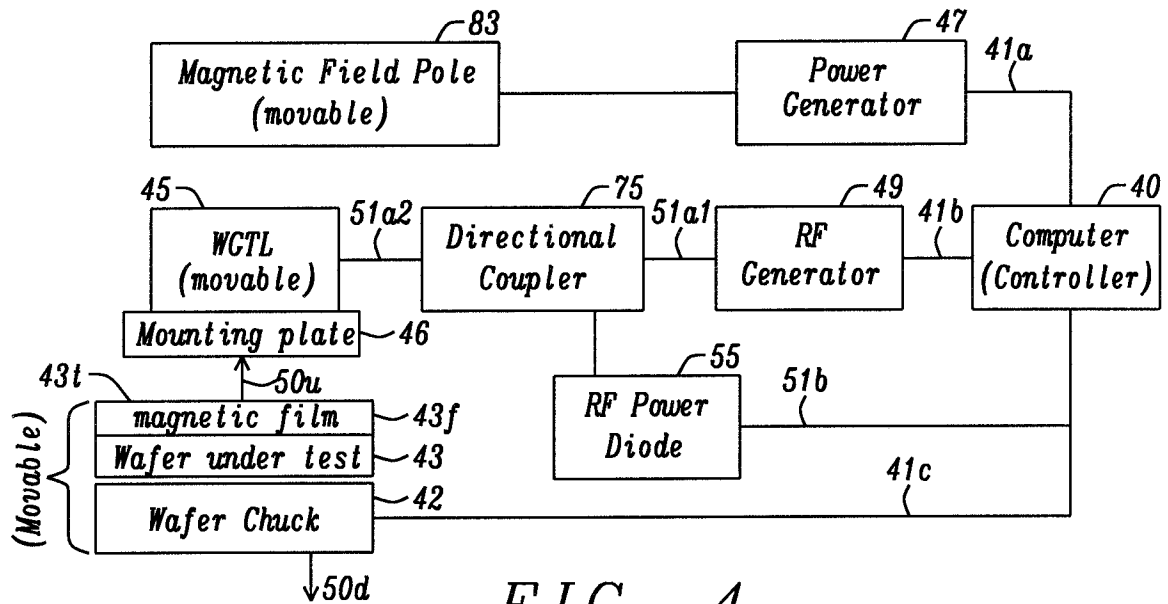


FIG. 4

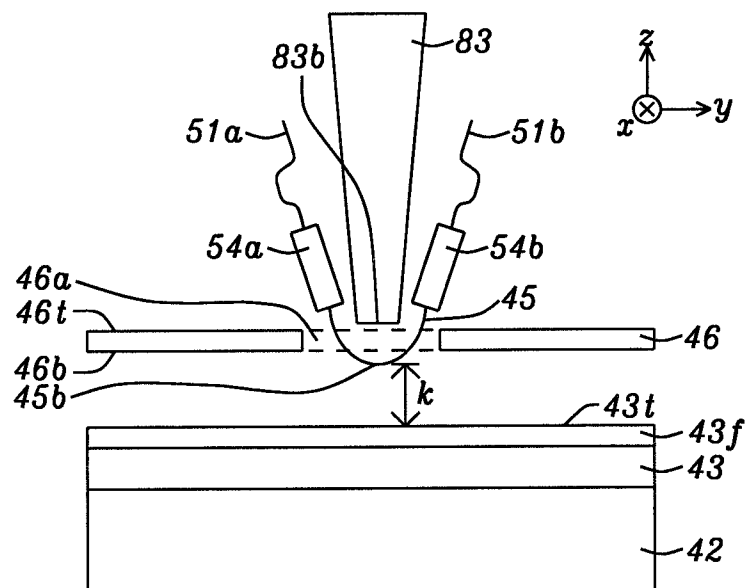


FIG. 5

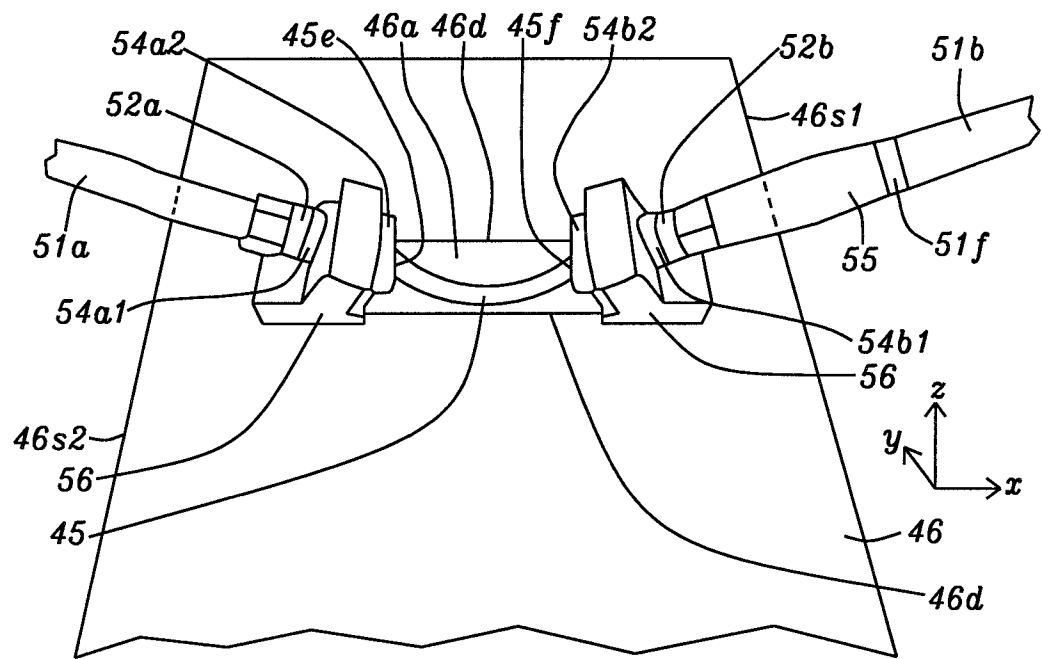


FIG. 6

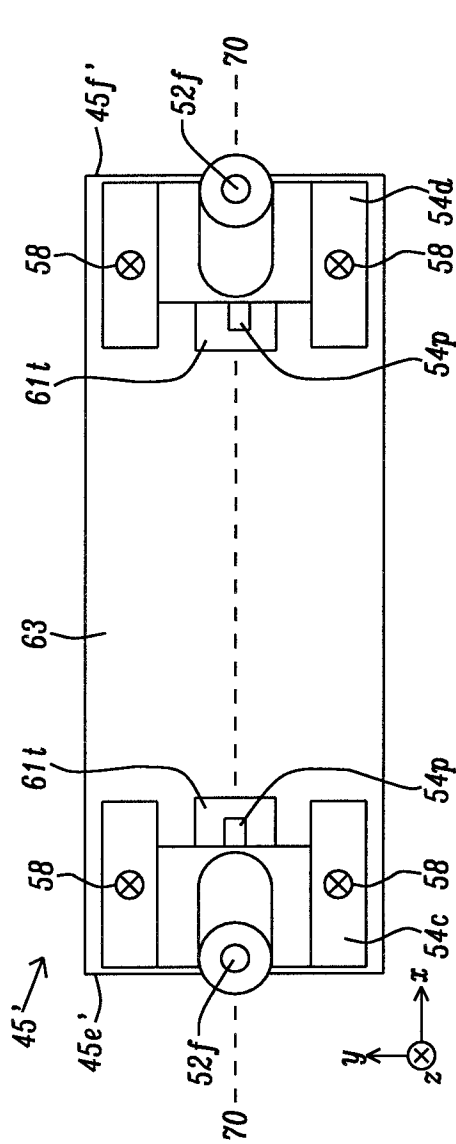


FIG. 7a

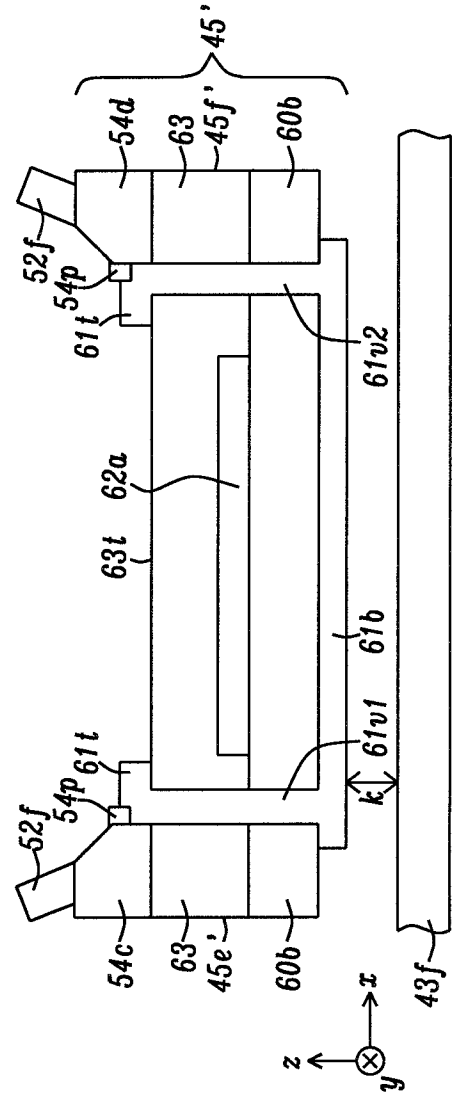


FIG. 7b

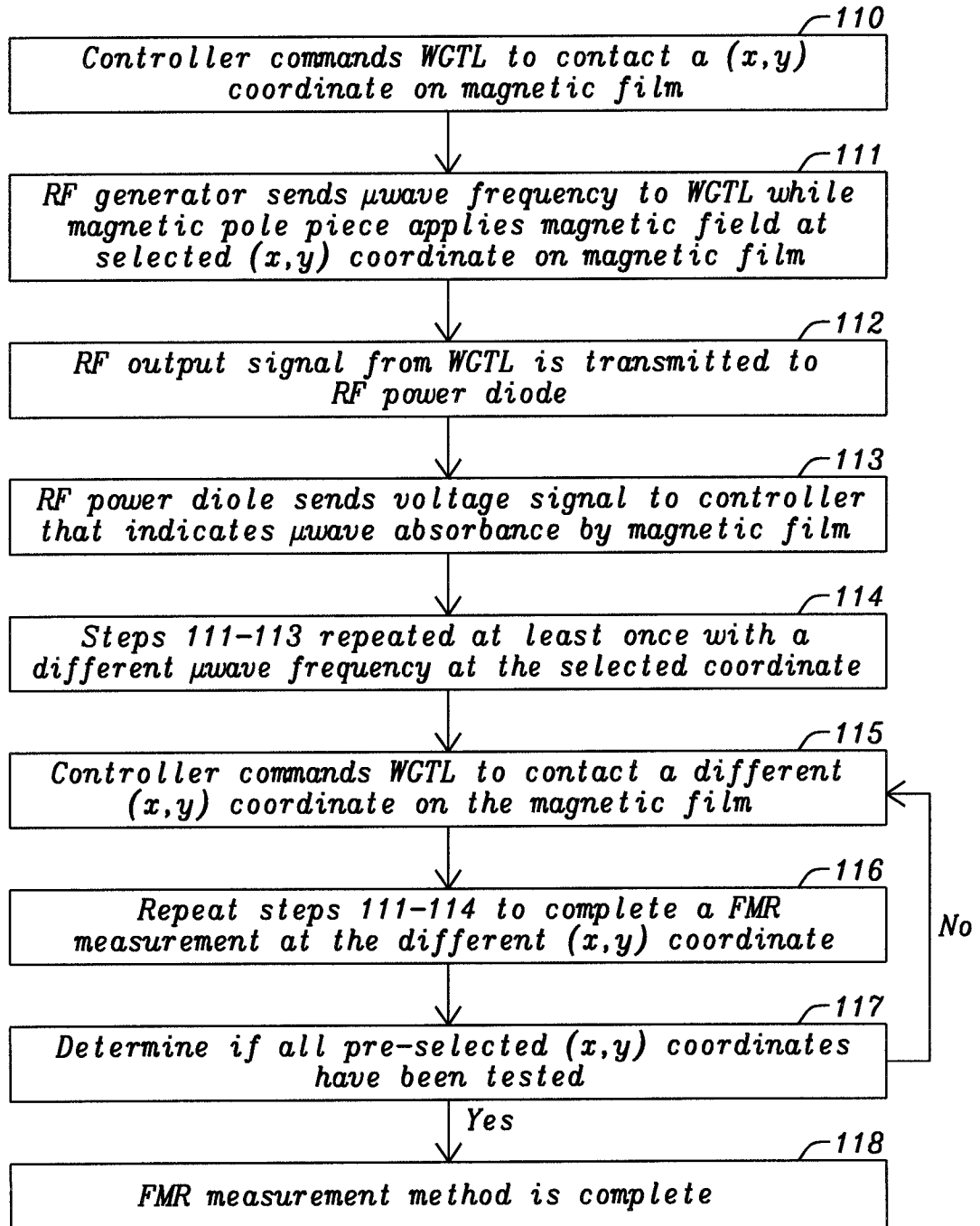


FIG. 8

		α									
FF_y		FF_z									
		4	6	8	10	12	14	16	18	20	
20					0.0109						
18			0.01	0.00989	0.0115	0.0113	0.0104				
16			0.0098	0.00902	0.0103	0.0102	0.0124				
14		0.0122	0.0101	0.00962	0.00955	0.00983	0.0132	0.0122			
12		0.0126	0.0104	0.0111	0.0105	0.00994	0.0119	0.0104			
10		0.0101	0.012	0.0102	0.011	0.0114	0.0117	0.0117			
8			0.0104	0.0101	0.0108	0.0119	0.011				
6			0.00891	0.00844	0.00883	0.00881	0.00851				
4					0.00966						

FIG. 10

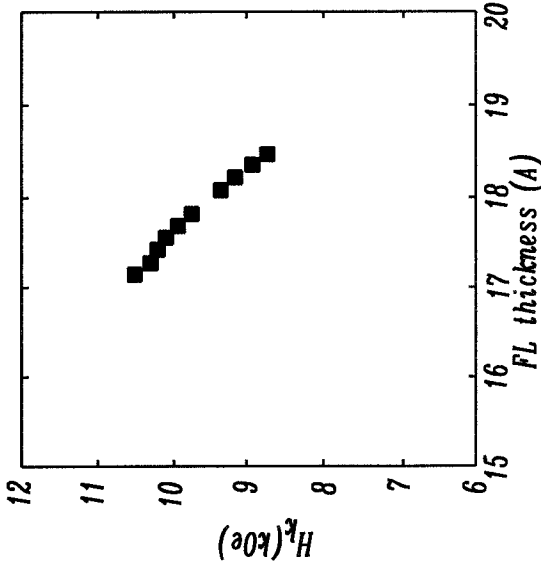


FIG. 11b

		$H_k(C)$									
FF_y		FF_z									
		4	6	8	10	12	14	16	18	20	
20					9.75						
18			9.78	9.77	9.75	9.74	9.75				
16			9.78	9.76	9.75	9.74	9.73				
14		9.75	9.77	9.76	9.75	9.74	9.73	9.71			
12		9.76	9.78	9.75	9.75	9.74	9.73	9.72			
10		9.74	9.75	9.75	9.74	9.73	9.7	9.7			
8			9.72	9.73	9.73	9.72	9.69				
6			9.69	9.7	9.71	9.69	9.67				
4					9.66						

FIG. 9

		$H_k(KOe)$									
FF_y		FF_z									
		4	6	8	10	12	14	16	18	20	
20					10.4						
18			10.5	10.3	10.2	10.1	9.97				
16			10.3	10.2	10.1	9.98	9.77				
14		10.3	10.2	10.1	9.94	9.78	9.58	9.36			
12		10.2	10.1	9.93	9.77	9.6	9.38	9.17			
10		10	9.91	9.75	9.59	9.37	9.19	8.96			
8			9.75	9.57	9.37	9.17	8.97				
6			9.52	9.35	9.16	8.95	8.76				
4					8.97						

FIG. 11a

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2018/020361

A. CLASSIFICATION OF SUBJECT MATTER

INV. G01N24/08 G01R33/30 G01R31/3185
ADD. G01R31/315 H01L21/66

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01N G01R H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, BIOSIS, COMPENDEX, EMBASE, INSPEC, IBM-TDB, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	MIRCEA DRAGOS ET AL: "Near-field microwave probe for local ferromagnetic resonance characterization", APPLIED PHYSICS LETTERS, A I P PUBLISHING LLC, US, vol. 90, no. 14, 2 April 2007 (2007-04-02), pages 142504-142504, XP012093952, ISSN: 0003-6951, DOI: 10.1063/1.2719241	1-5,9
Y	Whole document, in particular pages 142504-1 and 142504-2 and the last sentence of the first paragraph starting in right-hand side column on page 142504-3	6-8
A	----- -/-	10-40



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

28 June 2018

Date of mailing of the international search report

06/07/2018

Name and mailing address of the ISA/

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Authorized officer

Lebar, Andrija

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2018/020361

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	DAVID M POZAR: "Microwave Engineering 4th ed", MICROWAVE ENGINEERING 4TH ED, 1 December 2011 (2011-12-01), page 95,158, XP055486442, 2nd paragraph on page 95, 1st paragraph and table 3.6 on page 158 -----	6-8
X,P	WO 2017/171848 A1 (INTEL CORP [US]) 5 October 2017 (2017-10-05)	1-8, 22-25, 27,28, 30-40
A,P	abstract, sections "System Architecture", "Methodology" and "Further Example Embodiments"; figures 1a, 1b, 1c, 2a, 2b -----	9-21,26, 29

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2018/020361

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2017171848	A1	05-10-2017	NONE
