Perspective: Local ferromagnetic resonance measurement techniques: "Invited Review Article: Microwave spectroscopy based on scanning thermal microscopy: Resolution in the nanometer range" [Rev. Sci. Instrum. 79, 041101 (2008)]

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According to Vonsovskii,[1] ferromagnetic resonance (FMR) was unknowingly discovered by Arkad'yev in 1911.[2] The standard citation for the experimental discovery of FMR is to Griffiths[3] for his observation of the rather broad absorption profile and an "anomalous" electron paramagnetic resonance (EPR) field for in-plane magnetized electroplated ferromagnetic films. One year later, Kittel[4,5] explained the anomalous FMR fields by taking the dynamic demagnetizing fields into account. FMR is distinct from EPR because the FMR field or frequency is shifted from the usual range of pure electron spin resonance values by substantial amounts because of both static and dynamic demagnetizing field effects, among others.

The traditional approaches to the measurement of the FMR response are through shorted waveguide, microwave cavity, or stripline techniques.[6–8] One usually excites the FMR with a relatively uniform microwave field and obtains a uniform-mode or quasi-uniform-mode response in which all of the precessing spins are excited at the same nominal amplitude and in phase. In spite of the quasi-uniform-mode nature of the response, the actual power absorption profile for a large sample often depends on the local properties that may include a nonuniform microstructure as well as spatial variations in the local magnetic moment, gyromagnetic ratio, magnetocrystalline anisotropy, damping and relaxation processes, and so on.

From the late 1950s, various workers have also developed a variety of "local" FMR techniques. A local FMR experiment may be done in two ways. In the first, one excites the sample over a wide area and a local FMR probe is used for detection over a small region of the sample only. The second utilizes both local excitation and local detection. The first practical setup for local FMR measurements used the second approach, in which a thin film sample was excited and detected locally through a small iris of a microwave cavity. This basic and simple near field technique was developed independently by Frait[9] and Soohoo.[10]

From the initial work by Frait and Soohoo, there has been evolving work on local FMR approaches. Until recently, these have focused mainly on methods related to near field optics and based on the use of small probes. See Ref. 11 for a non-FMR related review of these general approaches. FMR related citations include work with small coaxial loop FMR probes[12–14] and dielectric resonator slit probes.[15] These methods represent fairly straightforward variations of the original Frait/Soohoo schemes at different levels of sophistication. These approaches have never been able to achieve spatial resolutions below about 10 μm or so.

In 1988, a new approach to local FMR based on thermal effects was introduced by Pelzl[16] at Ruhr University, Bochum, Germany. This method has led to a highly sensitive and very fine scale FMR measurement capability down to 10 nm or so. This technique may be termed "scanning thermal FMR microscopy" (SThM). For the conventional near field local FMR methods introduced above, a single probe plays a dual role in both the excitation and detection of the magnetic response. In the SThM technique, a microwave cavity is often used to excite the magnetic response in a wall mounted sample. A thermal sensor is then used to probe the sample through a small hole in the wall. The thermal probe simply measures the small changes in the local temperature that go along with the sample heating due to the FMR driven absorbed power.

The initial SThM system described in Ref. 16 was based on a photothermal modulation approach. The sample was locally illuminated by a 40 Hz power-modulated He–Ne laser with a 180 μm diameter spot size. The modulation induces a localized change in the magnetization of the sample, also at the 40 Hz modulation frequency. This, in turn, gives a modulation in the FMR power absorption and the corresponding local temperature that is then detected by lock-in detection methods. In recent years, Meckenstock *et al.* have made considerable advances in this basic local FMR thermal detection approach. Reference 17 describes extensions of the method to direct detection without thermal modulation. The nominal resolution in this case was about 100 nm. These authors also developed a variation of the method based on scanning thermal-elastic microscopy (SThEM). In this approach, the local thermal-elastic expansion is measured directly by atomic force microscopy (AFM) techniques.[17,18] This marriage of methods allows one to bring all of the power and advances in the field of AFM to the table for local FMR measurements. Compared to the previous near field FMR microscopes, the new thermal techniques give a significantly improved spatial resolution. The reported SThEM spatial resolution by Meckenstock *et al.* was in the range of 10 nm. The use of microwave power modulation and lock-in detection gave good sensitivity and a high signal to noise ratio.

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Further work by Sakran *et al.*[19] has combined the dielectric resonator slit probe discussed above and SThM techniques. In this case, the slit probe is used only for excitation, while a thermal probe is used for the detection of the FMR response. In this way, one can realize both the advantages of local excitation and the local resolution and sensitivity of thermal detection.

From the AFM connections discussed above, it is clear that the tremendous advances in AFM and related techniques from the 1980s forward[20] have played a critical role in the thermal local FMR probe work. As noted, AFM scanning stages and, in some cases, direct AFM measurements, can be employed to advantage for probe positioning as well as complimentary property characterization. These approaches allow for noncontact and nondestructive physical measurements with a resolution on the nanometer scale. The scope of this perspective does not include the non-FMR aspects of AFM technology. The interested reader may refer to recent reviews on scanning probe microscopy (SPM) techniques by Bottomley[21] and Wickramasinghe.[22]

This perspective is intended to introduce the extensive review paper on SThM and SThEM local FMR techniques by Meckenstock. As noted, these approaches have provided the highest local spatial resolutions obtained to date, in combination with high sensitivity, good signal to noise ratios, and ease of use.

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