

Synthesis and Integration Challenges and Approaches for Magnetic Materials and Devices in RF Electronics

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Abstract—Miniaturized magnetic devices such as circulators and limiters that could be monolithically integrated onto semiconductor substrates and their active devices would enable new, ultra-compact microwave and millimeter-wave systems on a chip. The many magnetic materials synthesis and integration challenges associated with this goal are described and reviewed. Prospective methods for overcoming these challenges are reviewed and discussed, based on the technical literature.

Keywords—ferrite; monolithic integration; magnetic materials; semiconductors; microfabrication; circulator; limiter

I. INTRODUCTION AND MOTIVATION

The marriage of semiconductor electronics such as amplifiers with magnetic-material-based components or devices such as circulators and limiters at microwave and millimeter-wave frequencies (generically referred to as RF) has traditionally been accomplished in a macroscopic fashion. On the largest scale, such assembly might consist of separate discrete and fixtured building blocks joined by coaxial connectors or waveguide joints. A more state-of-the-art middle scale level of integration involves incorporation of discrete magnetic components into a common fixture, package, or printed circuit board that also contains the semiconductor dies, and joining them together with wire bonding, flip-chip, or other “mesoscopic” packaging techniques. This method is typical of microwave and millimeter-wave power modules, and while it represents a significant improvement in miniaturization, the magnetic devices and their interconnects remain physically bulky and tend to dominate the overall size of the assembly.

Instead, if the magnetic devices could be further miniaturized and fabricated by compatible techniques that would allow them to be directly incorporated into the semiconductor dies (monolithic integration), then a profound reduction in system size and weight would be achievable. Furthermore, by virtue of this direct integration, entirely new types of ultra-compact RF systems and applications that were previously unrealizable or impractical would become feasible and cost-effective. These and related motivations have resulted in much new activity in academia and industry, as evidenced by a sharp increase in journal publications on this topic, as well as a new DARPA Magnetic Miniaturized and Monolithically Integrated Components (M3IC) research program [1].

There are a number of challenges to the monolithic integration between magnetic-materials-based components and semiconductor substrates and devices, which are mostly related

to materials synthesis and materials properties issues. These issues are reviewed in Section II. However, in spite of these challenges, there are a number of approaches for solutions that have appeared in the recent literature, web sites, or press releases; some of these techniques are reviewed in Section III.

II. REVIEW OF SYNTHESIS AND INTEGRATION ISSUES

One significant problem with monolithic integration is the gross difference in the conventional methods of creating high quality magnetic materials such as ferrites with those of semiconductors. The conventional synthesis of ferrites typically involves heating above 1100 °C in oxidizing atmospheres, which would severely damage any semiconductor devices and even the parent semiconductor material. Hence one either needs a lower temperature process or some means to separate the processing in a way that does no harm. Another problem is related to the traditional methods of forming the magnetic components that typically involves ceramic cutting and grinding of individual parts that can be difficult to reconcile with monolithic integration at the scale of semiconductor dies, hence more unconventional methods must be considered, perhaps before semiconductor devices are formed in the substrate. While the creation of thin films (a few microns or less) of ferrite and other magnetic materials on semiconductors has been accomplished by methods such as sputtering for a long time, or recently as very thin high quality epitaxial films by molecular beam epitaxy, such films are much too thin for RF devices, in which the electric and magnetic fields would be highly concentrated and would lead to prohibitively high losses in the materials themselves and in the surrounding metallizations. Instead, films need to be about 50-200 μm thick. Another key issue concerns magnetic orientation; magnetic materials of interest such as ferrites are anisotropic and the desired electromagnetic behavior such as non-reciprocity requires a proscribed orientation between the direction of the dc magnetic field, the film, and the RF magnetic fields of the signals (and transmission lines). Therefore, the magnetic materials must be capable of being deposited or processed in a manner that results in a specific orientation. Finally, the materials should be capable of being transversely patterned at the 10's of microns to the several mm scale on the semiconductors or otherwise grown within the semiconductor in a manner comparable to patterning.

A number of physical properties issues related to magnetic materials are also critical for successful device performance and these issues constrain the requirements for successful monolithic integration. For example, if one considers avoiding the high temperature sintering step and using a composite

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approach with magnetic material particles and a non-magnetic matrix, or some other means of low temperature particulate assembly, the resulting composite properties can be degraded by the matrix in certain microstructural arrangements that interrupt the continuity of magnetic material with large amounts of matrix or porosity. Another key physical issue is the need for a dc magnetic field to allow the materials and devices to function properly with respect to RF behavior. From an integration standpoint, this places a high priority on magnetic materials that are self-biased, meaning that they are capable of holding a remnant magnetization (~ 4 kG) by themselves with high coercivity (~ 4 kOe), so that they do not need an external magnet. Alternatively, one needs a means of synthesizing and microfabricating ancillary magnetic components (permanent magnets, soft magnetic circuit materials, etc.) in conjunction with non-self-biased materials. An important physical property that strongly impacts the desired RF performance is the ferromagnetic resonance (FMR) frequency of ferrite materials, which must be higher than the intended operating frequency and sufficiently narrow in width to preserve the desired non-reciprocal properties and to exhibit low losses. The combination of the desire for self-biasing and the push towards devices working at millimeter-wave frequencies makes the hexaferrite family of materials, particularly Ba and Sr hexaferrites, extremely promising candidates. The requirements also put further premium on the need for highly oriented films, since poor orientation will degrade the FMR frequency, broaden its width, increase losses, and limit the achievable remnant dc magnetic field.

III. APPROACHES FOR SOLUTION OF THE SYNTHESIS AND INTEGRATION PROBLEMS

A number of materials approaches that would enable high quality miniaturized magnetic devices and their monolithic integration with semiconductors have been put forward, and additional techniques are being explored, based on an assessment of the current literature and press releases. A number of broad themes have emerged, either individually or in various combinations. The methods include, but are not limited to, highly-loaded composites amenable to lower temperature processing, magnetic particle consolidation that does not rely on binders or high temperatures, processes of self-assembly or template-directed-assembly and orientation, additive manufacturing, and procedures of separating or mitigating the thermal stress issues of the magnetic material synthesis and the semiconductor fabrication in ways that still preserve the monolithic integration and functionality of both.

In the category of composites, one can consider polymer-magnetic material composites [2]. These could be formed with a monomer and polymerized in-situ by low level heat or ultraviolet light, or from a 2-part chemical reaction. With proper choice of particulate geometries and organization, high volumetric filling fractions can be obtained. There are also interesting opportunities for additive manufacturing using such materials. In the category of room-temperature particulate consolidation, a good example is the high velocity aerosol deposition technique [3,4], in which ferrite particles are entrained in a high velocity inert gas and sprayed onto a substrate or previously microfabricated electromagnetic

structures. The particles fracture and plastically deform into nano-scale grains with sufficient energy to self-sinter at room temperature into a dense polycrystalline film with thicknesses exceeding 10s or even 100s of microns.

Another low temperature method of consolidation applicable to ferrites is electro-consolidation of liquid-particle suspensions [5], with a process similar to electroplating but done with a colloid by electrophoresis. On a related note, permanent magnet materials such as CoPt have been successfully grown from dissolved salt solutions by means of electroplating [6], as have soft magnetic materials for use as pole piece and magnetic circuits [7]. This is particularly useful for materials that cannot be self-biased, or to raise the FMR to higher frequencies than that arising from native self-biasing.

Self-assembly can drive consolidation and/or aid in achieving orientation [8]. Applicable methods include driving forces based on van der Waals interactions, electric charge, surface tension, magnetic moments, particle shape, free volume, or entropy. Such assembly can be enhanced or tailored with externally applied entities such as magnetic or electric fields, thermal gradients, redox chemical potentials, or centrifugal forces. Another interesting variant is template-directed assembly, which can result in tailored microstructures to achieve further specialized properties or deliberate anisotropy. Templates can be structured polymers, ceramics, glasses, or biologics having either deliberately microfabricated features or structures arising naturally from template synthesis.

Finally, new methods of higher temperature magnetic material synthesis [9] and post-processing that are compatible with semiconductor substrates are also promising, with careful attention to thermal expansion, stress, and chemical issues.

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