Novel Nanostructured Passives for RF and Power Applications: Nanopackaging with Passive Components

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Abstract Miniaturization of passive components, while mounting them close to the active devices to form ultrathin high-performance power and RF modules, is a key enabler for next-generation multifunctional miniaturized systems. Traditional microscale materials do not lead to adequate enhancement in volumetric densities to miniaturize passive components as thin films or thin integrated passive devices. With these materials, component miniaturization also degrades performance metrics such as quality factor, leakage current, tolerance, and stability. Nanomaterials such as nanocomposite dielectrics and magneto-dielectrics, nanostructured electrodes, and the resulting thin-film components have the potential to address this challenge. This chapter describes the key opportunities in nanomaterials and nanostructures for power and RF passive components. The first part of this chapter describes the role of nanostructured materials for high-density capacitors and inductors in power modules. The second part of the chapter describes application of nanoscale materials as nanocomposite dielectrics and magneto-dielectrics with stable and high permeability and permittivity for miniaturized RF modules.

1 Introduction

Passive components are required in an electronic system for providing various power functions such as decoupling and voltage conversion, and RF functions such as filters, matching networks, resonators, and EMI isolation. The primary drivers for passive component evolution over the past few decades have been thickness reduction by enhancing properties and processing as thinner films and also provide

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X. Baillin et al. (eds.), *Nanopackaging: From Nanomaterials to the Atomic Scale*, Advances in Atom and Single Molecule Machines,
DOI 10.1007/978-3-319-21194-7_11

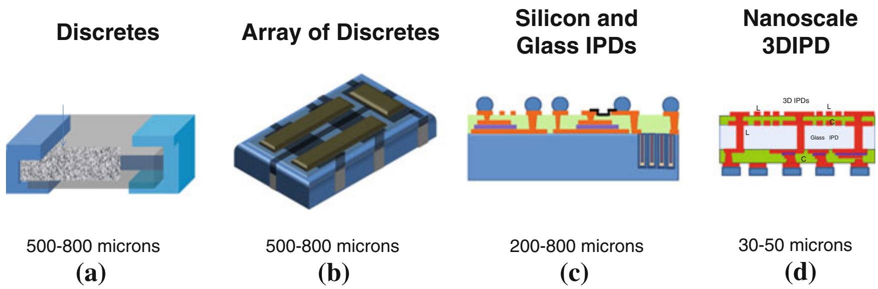

Fig. 1 Evolution of passive components from discretes to integrated passive devices (IPDs) and 3D IPDs

proximity to the active devices that they serve to provide these functions. These drivers have resulted in a continuous reduction in passive component thickness from 0.5 mm in the past to 0.15–0.3 mm with standards of 0201 and 01005 s, as shown in Fig. 1a, resulting in module thicknesses with passive and active components of ~ 1 mm. As these components are large and are mounted far from the active ICs, they add parasitics that scale with interconnection length and deteriorate the module performance [1].

Recent advances from discrete component manufacturers have enabled components of 100 micron thickness [2]. Such ultrathin passives have led industry to embed such discrete passives in the package buildup layers [3, 4] or assembled on the back of the package. This approach substantially reduces the package thickness and the distance to active devices to less than 200 microns, improves the module performance, and saves the package and board space. This approach is, however, limited by the component thickness (0.15–0.5 mm) and the number of components.

Passive arrays and integrated passive devices (IPDs) have evolved as an alternative approach to reduce the component count, footprint, and interconnect parasitics, as shown in Fig. 1b, c. IPDs with low-temperature cofired ceramics (LTCC) achieve the highest quality factors (Q) at GHz frequencies for RF interconnects and components, but cannot meet the reduced thickness needs. Silicon IPDs [5–7] (Fig. 1c) show high losses and do not meet the Q requirements for high-performance RF applications. Passive-integrated silicon substrates received more attention for power components as high-density capacitors or high-density inductors on silicon [8]. However, the limited properties and use of expensive semiconductor processes have been a major constraint in wider acceptance of this technology. Thin-film RF components are now being integrated onto glass substrates for enhanced Q and miniaturization [9]. These IPDs are fabricated on thick glass as one-sided components and are surface-mounted on the board as passive modules.

As the ultimate goal in system miniaturization and performance enhancement, institutes such as Georgia Tech. PRC and its industry partners, and semiconductor and packaging companies have advanced R&D in embedded thin-film passive technologies for the past two decades. The objective here is to integrate the passives as thin-film layers in the package buildup layers or in the ICs. However, embedded thin-film passives face several unresolved manufacturing issues related to achieving adequate capacitance and inductance densities, precision, testability, reworkability, and defect-driven yield losses.

Because of the manufacturing limitations with IPDs and embedded passives, functional modules in today's systems are predominantly made of discrete thick active and passive components that are connected with each other through a thick interconnect substrate with coarse-pitch surface-mount technology (SMT) interconnections. The overall impact of advances in active component to nanoscale on system size and performance is, therefore, limited by the passives that are mounted far away from the active components on thick organic or ceramic module substrate.

Nanomaterials provide several opportunities for simultaneous miniaturization and performance enhancement in power and RF passive components. The key requirements for emerging passive components are listed in Table 1. The table also shows examples of nanomaterials and nanostructures to meet these component requirements. Nanostructured materials result in 5–10× miniaturization in energy storage components for power components. They also alleviate the process compatibility issues, allowing multiple components to be integrated on a single glass substrate. Nanomaterials show superior electrical properties for capacitors and thus lead to miniaturized high-Q multilayer passives with higher dielectric constant and low TCC, wideband, and low-loss interconnects. They also show superior magnetic properties from improved exchange coupling between the domains, absence of leakage, absence of domain wall-assisted relaxation, etc. These nanostructures are expected to result in higher permittivity and permeability at much higher frequencies as compared to the current materials, leading to reduction in size and improved performance [10, 11] in board-compatible embedded antennas,

Table 1 Nanomaterials and nanostructures for passive component applications

	Properties	Nanomaterials and nanostructures
Power inductors	• Low coercivity: <0.1 Oe • High permeability: >100 • Loss tangent: <0.01 • Frequency stability: 10–100 MHz	• Metal nanocomposites • Nanogranular materials • Nanostructured ferrites
Power capacitors	• Volumetric density: >100 uF/mm^3 • ESR: <25 milliohms × µF • Leakage current: <10 nA/µF	• Nanoelectrodes; • Conformal nanoscale dielectrics
RF inductors	• $\mu_r > 5$ • Stability >1–10 GHz • Q > 100	• Metal nanocomposites; • Nanoscale hexaferrites
RF capacitors	• TCC: 30 ppm/C • Permittivity >20	• Nanocomposites • High-K super paraelectric fillers
Antennas	• $\mu_r \times \varepsilon_r > 10$; • $\mu_r/\varepsilon_r > 0.5$	• Metal nanocomposites; • Nanoscale hexaferrites
EMI isolation	• −60 dB isolation	• Metal nanocomposites

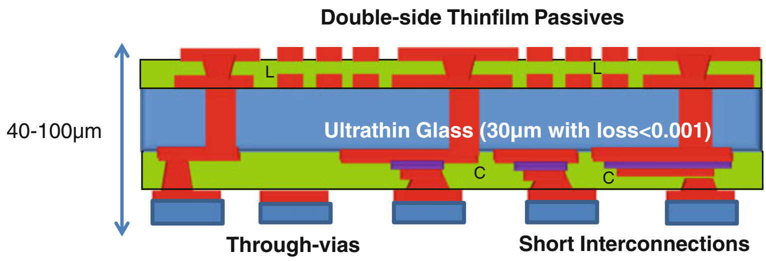

Fig. 2 3D IPD concept for power and RF applications

reconfigurable modules using MEMS, and nanostructured electronic band gap structures for RF-digital noise isolation. The need for nanomaterials in RF modules as capacitors, inductors, and antennas is compiled in the last four rows of Table 1.

2 Nanoscale 3D Integrated Passive Devices (3D IPDs)

Nanoscale passives combine the benefits of advanced thin-film passives with superior properties, thickness reduction with double-side components from through-vias, and mounted or surface-assembled with ultrashort interconnections on a thin substrate, evolving into a new class of 3D integrated passive devices or 3D IPDs. The schematic 3D IPDs for RF applications are shown in Fig. 2. In a RF 3D IPD, high precision and high-Q inductors and capacitors are formed on a through-via glass substrate with thin-film buildup layers. Similarly, power 3D IPDs can also comprise of high-density power inductors and capacitors, and thin-film capacitors on a thin glass substrate with through-vias. In terms of passive component integration, 3D IPDs go beyond the state of the art in many ways—novel thin-film materials and processes for higher volumetric density; quality factor and voltage, frequency, or thermal stability; ultraminiaturized and testable RF; and high-performance module by virtue of closest proximity between actives and passives.

These 3D IPDs, in turn, result in ultrathin 3D integrated passive and active component (3D IPAC) functional modules with 3–5× reduction in size and 2× reduction in cost compared to today's bulky discrete functional modules [12].

3 Nanoscale Power Components

3.1 *Power Inductors*

Thin-film inductors require magnetic cores with higher permeability, field anisotropy, low coercivity, and frequency stability. Today's magnetic materials for power inductors face several shortcomings toward these requirements. Even though ferromagnetism, which is a well-known phenomenon that results in high permeability and high saturation magnetization, exists in metals such as Co, Fe, and Ni, these are not suitable for high-frequency applications because of their high electrical conductivity that leads to eddy current losses. Ferrites are based on oxides of these metals and have higher electrical resistivity, thereby being more suitable for power inductor applications. Spinel ferrites (e.g., $NiFe_2O_4$, Mn–Zn and Ni–Zn ferrites) [13, 14] are extensively used in power converters because of their lower losses than metal cores, resulting in high-Q factors at moderate frequencies of 100 kHz–1 MHz. However, for emerging high-frequency consumer applications, ferrites suffer from several major disadvantages, including low saturation magnetization and poor frequency response of magnetic properties due to their strong relaxation behavior. These limitations lead to millimeter size components and thus make ferrites unsuitable for emerging applications.

Metal–polymer composites, in contrast, can address this problem because of their higher saturation magnetization while retaining higher resistivity. These composites consist of metallic magnetic particles that are coated (or separated) by an insulating phase. Such magnetic powders in polymer paste form are commercially available from various vendors. Examples of these include iron and permalloy powders, which show permeabilities of 40–100 in the low MHz frequency range [15]. However, these materials show insufficient permeabilities and unstable properties beyond 10 MHz, which limits them to lower frequency applications only.

Magnetic nanocomposite materials are comprised of nanoscale magnetic particles in an amorphous matrix. Such materials provide unique opportunities to address the fundamental limitations of traditional magnetic materials, as shown in Fig. 3. Higher permeability in magnetic nanocomposites at microwave frequencies can be achieved by reducing the particle size and the separation between neighboring metal particles down to the nanoscale, which leads to novel magnetic exchange coupling phenomena [16]. For example, Co- or Fe-based nanocomposites show much higher permeability and frequency stability at microwave frequencies than those obtained from the bulk Co or Fe metal or their microscale composites [17]. The exchange coupling interaction, which is attributed to the magnetic ordering within grains, also extends to neighboring grains within a characteristic

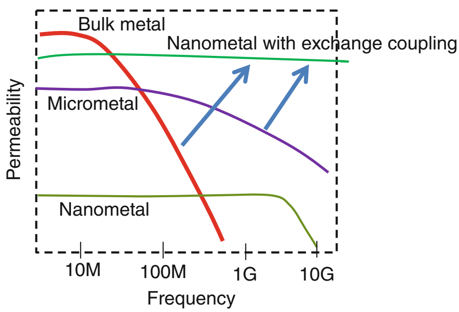

Fig. 3 Nanomagnetic composite structure and its benefits

distance, l_{ex} [18]. The exchange interaction in nanocomposites also leads to the cancelation of magnetic anisotropy of individual particles and the demagnetizing effect, leading to improved soft magnetic properties [17]. Because of the nanosized metal particles, the eddy currents produced within the particle are also negligibly small, leading to much lower loss for nanocomposites, compared to that of conventional microsized ferrites and powder materials.

Magnetic cores with sputtered high-resistivity nanogranular alloys such as Co–Zr–Ta, Co–Hf–Ta–Pd, and Co–Zr–Nb can increase the frequency stability and quality factor. Inductors displaying 0.05–0.15 $\mu H/mm^2$ at 1–2 MHz [19, 20] are reported with such cores. On the other hand, in the pioneering work by Intel on on-chip power inductors, nanolaminates with spiral coils showed inductance densities of up to 2.0 $\mu H/mm^2$ at 500–1000 MHz, 10× higher than the state of the art [21]. Their work demonstrated that nanolaminates can increase the roll-off frequency from 300 to 800 MHz. These inductors take advantage of the uniaxial magneto-crystalline anisotropy in the magnetic core surrounding the spiral inductor coils. However, the power handling with these inductors is limited unless the inductor thickness is increased to several microns, which requires new innovations in nanomagnetic synthesis.

3.2 Power Capacitors

Multifunctional systems for mobile and high-performance computing typically operate with multiple power rails on multiple voltage levels. Capacitors are widely employed for voltage conversion and ripple-free voltage supply over a broad frequency range. In a typical power distribution network (PDN), multiple capacitors are incorporated at different levels of the system to provide the decoupling function. Today's discrete capacitors can only address decoupling needs in a narrow frequency band. This typically increases the number of discrete capacitors, thus the package size, and also limits the high-frequency performance. The trend to capacitor array with multiple components can address this challenge to some extent by patterning the capacitors into multiple sizes but presents other limitations related to thickness, cost, proximity to active devices, and other design constraints from the low capacitance densities.

The volumetric density of available discrete capacitors has not caught up with the demand for high-density capacitors in integrated thin power modules. This is because of several fundamental limitations with existing capacitor technologies. The capacitance density is directly dependent on the electrode surface area, dielectric permittivity, and thickness. Today's high-density capacitor technologies suffer either from low surface area because of the microscale electrodes or from low permittivity of dielectrics, or both. Tantalum capacitor technologies provide high surface area enhancement, but the dielectrics are limited to tantalum pentoxide with a permittivity of about 25 [22, 23]. With nanoscale tantalum electrodes, the capacitance volumetric density can be further increased but degrades the equivalent series resistance (ESR) and frequency stability. On the other hand, multilayered ceramic capacitors (MLCC) do not have adequate area enhancement because of limitations of ceramic and metal thick-film technology [24]. The trend toward silicon trench capacitors provides limited area enhancement because of the limitations of silicon micromachining technologies. Conformal coatings with atomic layer deposition (ALD) on such deep trenches are another major challenge [25, 26], while thermal oxidation or nitridation limits the dielectrics to lower permittivity values.

Nanoparticle electrodes provide much high surface area compared to trench capacitors and are currently being developed to improve the capacitance density by a factor of 10× at lower cost using scalable materials, tools, and processes. [27]. The porous electrodes with partially sintered nanoparticles provide ultrahigh surface area per unit volume resulting in area enhancement of above 1000× for a 50 micron thick film. Capacitance densities of above 400 $\mu F/cm^2$ have been demonstrated with breakdown voltages exceeding 15 V for a component thickness of 50–70 microns [28].

The capacitance density can be further improved with ultrathin dielectrics of 20–30 nm. High capacitance density with nanoscale dielectrics usually leads to high leakage current in a capacitor which is detrimental to its performance and reliability. This can be addressed by using conformal and uniform or self-limiting dielectric with least defect density. A conformal and uniform dielectric deposition can be achieved using ALD. However, ALD is an expensive process with high deposition time and low throughput, particularly with porous electrodes that require long diffusion times. On the other hand, nanoelectrodes using valve metals can be readily oxidized by immersing the nanoelectrodes in an electrolytic bath while subjecting the nanoelectrode to a potential bias. This process is known as anodization and has been widely used in the electrolytic aluminum and tantalum industry.

Leakage current can be further minimized by using self-healing cathodes. The self-healing works on the principle of isolating the cathode next to the defect site in the dielectric such that no current flows through the site thus preventing a short. Manganese oxide (MnO_2) and conductive polymers such as PEDOT:PSS are the most widely used self-healing cathodes in the tantalum capacitor industry. MnO_2 is formed by dipping the dielectric-coated high surface area electrodes into an aqueous manganese nitrate ($Mn(NO_3)_2$) solution followed by thermal annealing. Multiple impregnations and annealing cycles are employed for conformal MnO_2 coating over the high surface area architecture. However, MnO_2 has a lower conductivity ($\sim$10 S/cm) than PEDOT:PSS ($\sim$100–600 S/cm) leading to higher electrode resistance and ESR, as compared to polymer-based capacitors.

ESR in MnO_2 can be lowered by carefully controlling the oxygen levels during the reaction to prevent the formation of resistive manganese oxide (Mn_2O_3). This leads to the formation of dense, smooth, and uniform manganese dioxide layers with higher electrical conductivity. Introduction of oxidizing agents such as nitric acid, hydrogen peroxide, and ozone during the annealing of $Mn(NO_3)_2$ was explored for forming highly conductive and conformal MnO_2 layer with lower ESR [29].

Use of alternative organic polymers such as thiophene-based PEDOT, with higher conductivity, better ESR, and ease of processibility, is being actively used in tantalum capacitor industry. Conducting polymer such as poly (3-hexylthiophene-2,5-diyl) or P3HT is another potential candidate that could be explored for use as cathode. The conductivity of P3HT is in the range of $\sim 10^3$ S/cm, which could be further enhanced by the addition of endometallo fullerene or phenyl-C61-butyric acid methyl ester (PCBM) [30, 31]. However, the self-healing capabilities of P3HT as a cathode are still a subject of investigation for the researchers.

GT-PRC has recently demonstrated novel approaches for integrating nano-structured electrodes and conformal nanoscale dielectrics on silicon or non-silicon substrates leading to ultrathin capacitors. The first approach involves low-temperature sintering of base metals such as copper directly on silicon to form porous copper electrodes as anodes. Alumina is conformally deposited over the porous copper electrodes using the process of ALD followed by dispensing of conducting polymer as cathode [32]. In the second approach, etched valve metal foils were evaluated as a high surface area electrode, followed by anodization process for dielectric deposition. The electrochemically etched Al foils with high aspect ratio of above 50 were anodized to form conformal, thin aluminum oxide dielectric. In both the approaches, PEDOT:PSS was used as the cathode material which was coated conformally using simple solution dispensing methods. High surface nanoscale tantalum electrodes were also integrated on silicon substrates as an alternative anode structure. The advances have shown capacitance densities of 100 μF/cm^2 using silicon or package-compatible processes. The approaches are schematically illustrated in Fig. 4.

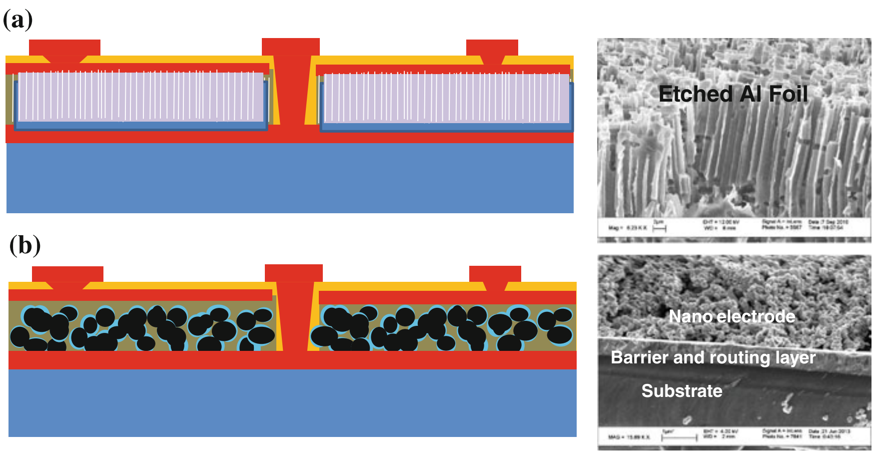

Fig. 4 Two approaches for integrating high-density nanocapacitors in 3D IPDs. **a** Etch foil. **b** Nanoparticle electrode

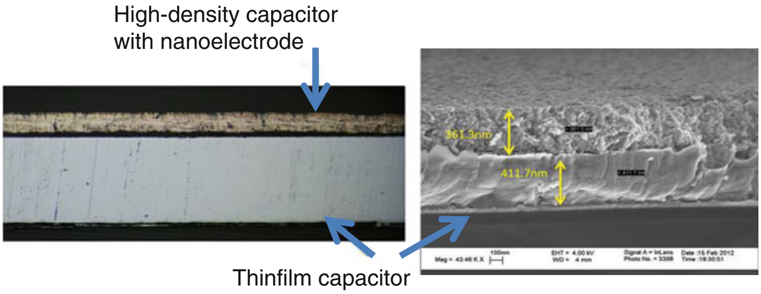

Fig. 5 3D IPD with high-density and thin-film decoupling capacitors

Several advances have been made in integrating thin-film decoupling capacitors [33, 34] for more than a decade. These include high-K dielectrics with silicon, glass, or organic substrate-compatible processes for high-permittivity films both as ceramic thin films and ceramic–polymer composites. The 3D IPD capacitor approach takes these thin-film capacitors and high-density nanostructured capacitors further by integrating them on a single substrate with through-vias. The 3D IPD capacitor network will have nanoelectrode capacitors (1 μF/mm^2) on one side for decoupling at low–mid frequencies and high-permittivity thin-film capacitors (20–30 nF/mm^2) on the other side at higher frequency bands, as illustrated in Fig. 5. Further, it gives better performance than embedded thin-film decoupling capacitors because of the close proximity (<40 microns) between the active and 3D IPD passives, as shown in Fig. 2. The devices can be tested before assembling on the 3D IPAC substrate. Advanced glass-based 3D IPDs with high dielectric constant thin films using glass-compatible processes have been developed [35, 36] to achieve this goal.

4 Nanoscale RF Components

4.1 RF Capacitors

Miniaturization of RF components such as filters, oscillators, matching networks in amplifiers, and antennas, operating with high performance at GHz frequencies, needs materials with higher permittivity and permeability, along with stringent tolerance in dielectric and magnetic properties, low temperature coefficient of permittivity (TCK), and low-loss tangent (Df). Over the past few decades, high-frequency components were therefore mostly confined to thick-film LTCC, owing to its low loss, stable properties, and partial integration capability, although the end-systems were bulky and costly [37, 38]. Polymer dielectrics, on the other hand, provide the benefits of low-cost manufacturing and the capability to integrate completely with the rest of the polymer-based system. RF components from low-loss polymers such as liquid crystal polymer (LCP), bisbenzocyclobutene (BCB), and polytetrafluoroethylene (PTFE) are now integrated to meet the stringent

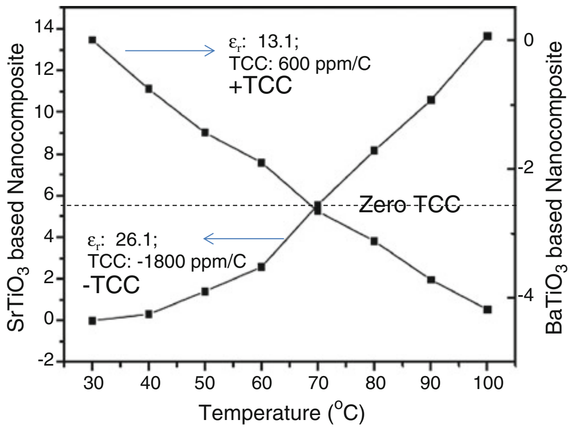

Fig. 6 Nanostructured dielectrics with high-K and low loss, but with opposite TCC, that can be used for compensation

requirements of high-performance systems. The low dielectric constant of such materials, however, leads to relatively larger component designs and is a major barrier for miniaturization and performance of wireless interfaces. Several substrate companies are now focusing on developing novel RF substrates by incorporating low-loss paraelectric-like high-K fillers in PTFE-based materials. These high-K and low-loss RF substrates are good candidates for miniaturizing certain RF circuits. However, they do not meet the temperature coefficient of capacitance (TCC) and low-loss requirements for several other applications. Any increase in the dielectric constant is accompanied by a strong dependence of capacitance with temperature, frequency, voltage bias, and film thickness.

For miniaturized RF components, nanocomposite materials based on nano-structured superparaelectrics provide new avenues for high permittivity, low loss, frequency stability, and low TCC [39]. Ferroelectrics at nanoscale show linear permittivity behavior with temperature, but with either +TCK or −TCK depending on the phase transition temperatures. These fillers can be used to effectively compensate the net TCC as illustrated in Fig. 6. By incorporating paraelectric fillers into the low-loss buildup layers, composites with permittivity 3–4× higher than the polymer matrix have been achieved with low TCC [40] even with traditional organic buildup layers. Novel high-K thin-film RF dielectrics based on glass-compatible nanostructured superparaelectrics that can enhance the permittivity without compromising stability and loss [41] are now being developed.

4.2 RF Inductors

Major fundamental and technological advances in the design and fabrication of high-frequency inductors have been demonstrated [42]. In combination with low-loss polymer buildup dielectrics (dielectric loss of 0.002) and polymer core substrates, multilayered inductor structures can be built without significant degradation in Q. RF inductor design libraries for high-density, Q of above 200, and self-resonant frequency (SRF) of above 10 GHz were built with various substrate geometries and design rules. Glass is a much superior material for high inductance density and Q because it combines the benefits of (a) ceramics for ultralow loss, (b) organics for large-area and low-cost processing, and (c) silicon for high density and precision coil definition. Planar spiral inductors designed with sufficient distance from the ground planes resulted in an inductance density of 50 nH/mm^2 and Q of above 60 on glass substrates [43]. Higher inductance density without compromising losses from the coil resistance, however, remains to be achieved.

For higher inductance densities with high Q, low-loss and high-permeability dielectrics are desired. However, magneto-dielectrics with stable permeability and low loss in GHz frequencies are not currently available. Magnetic materials suffer from eddy current and domain wall losses, which make them unsuitable for frequencies above 100 MHz. To enhance frequency stability, the materials should have single-domain nanosize particles with suppressed eddy current and domain wall losses. However, such materials usually show low permeabilities unless the nanoparticles are densely packed to enable exchange coupling between them. The frequency stability of permeability with micro- and nanoscale materials is schematically illustrated in Fig. 7. Nanogranular materials or nanoscale thin films have been shown to have frequency stability with permeabilities of above 100 [44, 45]. These materials will find applications in RF inductors in thin film form because of their low-temperature sputter processing that is compatible with large glass panels.

Certain hexaferrites are also emerging as promising candidates for high-frequency applications [46]. These materials show high crystal field anisotropy leading to high FMR, with the combined advantage of low eddy current losses. The large particle size during ferrite processing at high temperatures, however, leads to

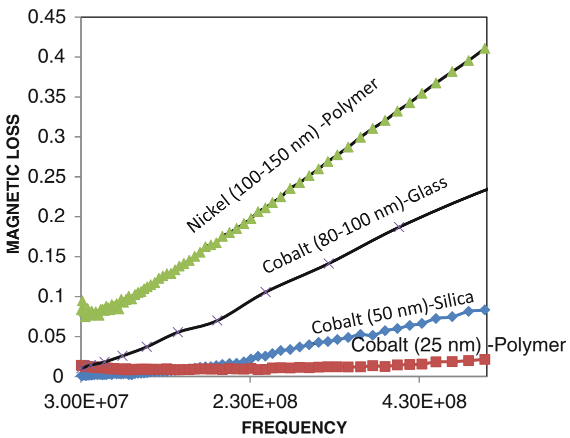

Fig. 7 Role of nanostructured materials in frequency stability

higher losses and instabilities presumably from domains. Efforts to suppress grain size with glass additives were shown to yield lower loss in 2–3 GHz range [47].

4.3 Filters

Filters from 3D IPDs with double-side inductor and capacitor components, going beyond today's silicon IPDs in improving the performance and component density, were recently demonstrated [43, 48]. The ultralow dielectric loss in glass enables the highest quality factors, superior to that of ceramic or organic modules, but with much higher integration and component density, low substrate and interconnect loss, at low cost. Through-via formation using low-cost packaging tools and processes such as laser vias and wet metallization techniques was utilized for interconnecting the components on both sides. Typical second-order filters show an insertion loss of less than 1 dB and return loss of above 25 dB. With the potential advances in nanoscale dielectrics and magneto-dielectrics described in Sects. 4.1 and 4.2, much superior performance and miniaturization are anticipated in the future.

4.4 Antennas

Antenna size has been a major bottleneck for reducing the size of RF front-end modules. The antenna dimensions are proportional to $1/\sqrt{\varepsilon\mu}$. The antenna size can be reduced by surrounding it with a material of either high permittivity (ε) or permeability (μ), thus leading to miniaturized designs. Thin antennas, however, suffer from relatively narrow bandwidth, substrate dielectric loss, mutual coupling with their substrate, and surface wave perturbation issues [10].

Nanoscale magnetic composites offer both higher permittivity and permeability and therefore offer superior antenna performance as measured by bandwidth and gain while also allowing miniaturization. Metal–polymer nanocomposites with both high permittivity and permeability for miniaturizing antennas have been studied by GT-PRC [49] and its partners. The nanomagnetic antennas showed 80 % reduction in size compared to traditional polymer substrate antennas.

5 Summary

Passive components for power and RF functions have been limiting the performance and miniaturization of electronic and bioelectronic systems. The inferior properties with these materials limit the component miniaturization, and hence, these components are not integrated into active silicon CMOS devices or in packages. They are currently assembled as milli- or microscale components on the packages and boards.

Among the passives, magnetic components such as inductors and antennas have remained as the biggest bottleneck because of the limitations of traditional magnetic materials such as ferrites and microscale metal composites. Nanomaterials are emerging to address the fundamental limitations of today's magnetic materials. By designing the magnetic structures at nanoscale, simultaneous high-frequency permeability with low losses and power handling can be achieved. These nanomagnetic materials can thus transform today's bulky discrete magnetic components to integrated planar thin-film structures, resulting in simultaneous size reduction and performance enhancements. Similarly, nanoscale dielectrics and energy storage devices such as capacitors also increase the volumetric density with electrode surface area, high permittivity, high frequency, and thermal stability.

The superior properties of nanomaterials and their processability as thin-film 3D IPDs enable revolutionary advances for several power and RF applications such as high-density capacitors, inductors, filters, resonators, matching networks antennas, and EMI isolation structures.

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