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Micromachined Intermediate and High Frequency Inductors

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Abstract

The use of inductors in electronic circuitry is widespread, especially in analog applications such as filters, tuners, and wireless communcations systems such as cellular telephones and pagers. Often the number of passive components in such applications greatly exceeds the number of silicon chips, thus making desirable the ability to integrate the passive components in the same manner as transistors are currently integrated. Because the passive components are often relatively large in size, it can be more appropriate to integrate these devices into the *package* rather than on the chip. This paper describes several methods for integrating intermediate and high frequency inductive components with low temperature multichip module laminate substrates, with the goal of achieving lower cost and smaller size than current packages with hybrid-mounted inductors.

Introduction

The microfabrication of passive components (including resistors, inductors, capacitors, and piezoelectric components) represents an important roadblock to the miniaturization of many electronic products. Heavy reliance on analog circuitry requires a large number of passive components to be used in consumer products such as VCRs, camcorders, television tuners, and cellular telephones. For example, in a typical video camera currently manufactured by Hitachi, there are 475 passive components required. Current development plans will reduce that number to 290 before the year 2000, as illustrated in [1]. Continued miniaturization is expected to reduce power consumption as the number of ICs and passive components are decreased for smaller and lighter products. However, the basic approach of mounting these miniaturized components on boards and modules in a hybrid fashion will continue. This evolutionary approach to miniaturization, involving hybrid mounting of individual passives, not only adds to the expense of manufacture, but more importantly also limits sharply the total board miniaturization which can be achieved. In addition, hybrid mounting of passives unavoidably introduces additional parasitics into the system, which limit system performance and/or increase the value and size of the passive elements needed. A logical approach to addressing this issue is *integrating* these passive elements directly into a multichip module (MCM) substrate, while at the same time maintaining the low-cost nature of the MCM process. This integration yields two major benefits: reduction in size of board by as much as 80 percent, as now chips can be mounted over these low-profile thin film passive devices; and reductions in parasitics due to the elimination of leads. Resistors, inductors, and capacitors as well as other passive elements, such as variable elements and switches, are all candidates for MCM integration.

There has been much work in realizing integrated passives in both MCM-C (ceramic-based) and MCM-D (deposited) strategies [2-6]. However, the work described here takes a different approach. We have been working in conjunction with the National Science Foundation Engineering Research Center in Electronic Packaging at Georgia Tech. The vision of this center is to realize *low-cost* solutions to packaging problems by utilizing large area processing and polymeric (e.g., laminate or MCM-L) substrates. These materials (such as the standard epoxy-glass composite) have the advantage that large areas can be realized inexpensively; however, all subsequent processing steps must be low temperature. This additional constraint of low temperature (less than 230 °C) does not allow us to use many of the solutions for integrated passives developed for the MCM-C and MCM-D approaches. In this paper, the work ongoing for the realization of integrated inductors using low temperature fabrication techniques is described.

Integrated Ferrite Inductors

The incorporation of ferrite materials into micromachined inductors enables both a potential for increasing the inductance and quality factor (Q-factor) as well as for shielding of electromagnetic radiation, particularly important as highly spatially integrated passive elements may otherwise have substantial crosstalk. There has been success in utilizing fired ferrite inks for incorporation of ferrites in inductor structures. However, to be compatible with organic

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substrates, low temperature approaches are required. Much research has been performed for the deposition of ferrite films at low temperature, e.g., using spin spray coating, electroplating, RF sputtering, and magnetron sputtering [7-9]. However, these methods have relatively low deposition rates and usually produce thinner films than required. Thicker films are necessary to achieve high inductance, quality factor, saturation current, and other good performance characteristics in integrated inductors and transformers [10,11]. The purpose of this study is to investigate fabrication techniques which are compatible with organic packaging to create integrated magnetic components for miniature DC/DC converters and other power supply applications. We have elected to pursue a filled polymer approach, in which ferrite powders are incorporated into a polyimide matrix to create 'plastic' magnetic structures. The materials used are described in detail in [12,13].

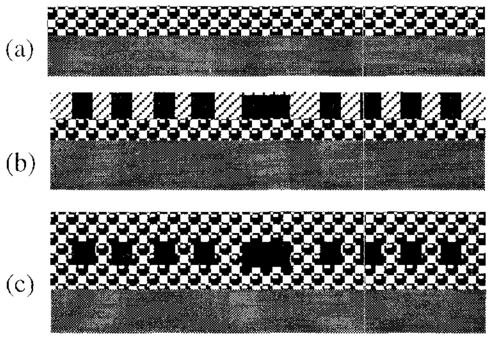

Fig. 1. Fabrication steps of EMI shielded spiral type ferrite inductors; (a) Composite material is screen-printed on glass, (b) Plating mold is formed and filled with plated copper, (c) Mold is removed and composite is screen-printed

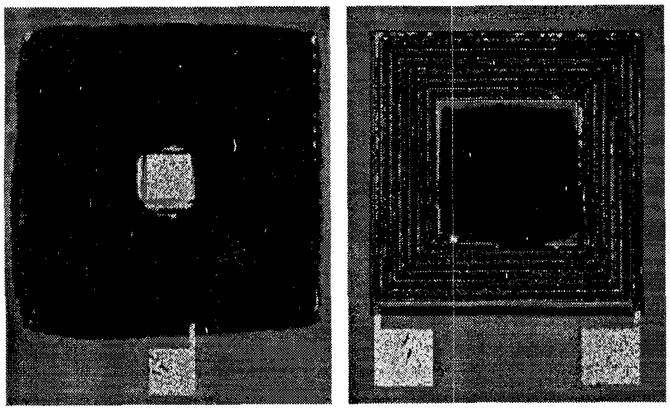

Fig. 2. Photomicrograph of EMI shielded spiral type ferrite inductors (dimension: 2.6mm x 2.6mm x $60\mu m$). Left: single-layer coil. Right: multilayer coil.

Figure 1 shows a brief fabrication sequence of the EMI shielded sandwich type spiral inductor. The process started with a glass substrate, which is both low cost and low dielectric constant compared with silicon. Polymer filled ferrite was deposited on the substrate by screen printing. The screen printed magnetic material was cured at 200-300 °C for 1 hour in nitrogen. Chromium/copper/chromium layers were deposited to form an seed layer for electroplating using electron-beam evaporation. Thick photoresist was coated, and molds were formed. After removing the top chromium layer, copper was electroplated into the photoresist molds to form the spiral conductors, and the molds were removed. The seed layer was wet-etched to isolate the conductor lines. Polymer filled ferrite was screen printed on the top of electroplated copper conductor lines and between the conductor lines, and cured to remove the solvents. Upon completion of the fabrication, the samples were diced and tested. Figure 2 shows fully fabricated devices. The extension of this technique to multilayer coils is straightforward, as shown in Figure 2.

The inductance and Q-factor of the fabricated inductive components were measured by a Hewlett-Packard impedance/gain-phase analyzer 4194A. For sake of comparison, on each data chart the inductor incorporating ferrite was measured relative to a control sample which does not incorporate ferrite to assess directly the beneficial effect of the ferrite material. Figures 3-4 show the inductance and Q-factor characteristics of single layer spiral coil inductors with air core and sandwich type spiral inductors with polymer filled ferrite core as a function of frequency and show that the inductors incorporating polymer filled ferrite have higher inductance and quality factor than the corresponding air core inductors. The increase of the width of the conductor and the decrease of the spacing between the conductor lines produces higher inductance and quality factor. Figures 5-6 show the inductance and Q-factor characteristics of the two layer spiral coil inductors with and without polymer filled ferrite core as a function of frequency and also verify the improved performance of integrated inductors with polymer filled ferrite cores. The measured Q-factor is high (15-17 at 15 MHz), and due to the material properties, higher Q-factors at higher frequencies are expected. Ferrites with better magnetic properties than those used are expected to yield even more favorable results.

Integrated High Frequency Inductors

In addition to the ferrite inductors described above, there is need for lumped integrated inductor and transformer components for filters, tuners, impedance matching, and other applications, fabricated in such a way that they can be directly integrated with the fabrication processes of multichip modules (MCMs), and able to operate in the frequency range of 100 MHz to several GHz. Current circuit technology recognizes a gap in the lower frequency end of operation (1-5 GHz) where distributed inductive components (such as quarter-wave matching stubs and stripline discontinuities)

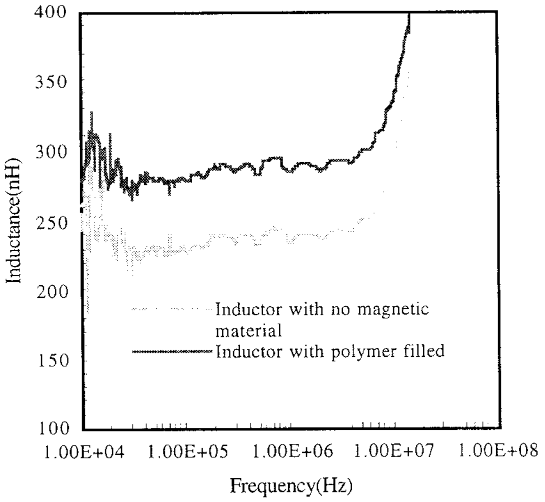

Fig. 3. Comparison of inductance of single layer spiral type inductors with and without composite material (width of conductor line: 30μm, spacing between lines: 50μm, number of turns: 13)

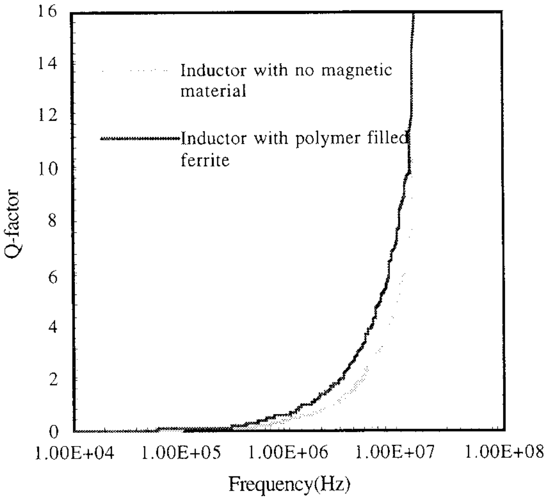

Fig. 4. Comparison of quality factor of spiral type inductors with and without composite material (width of conductor line: 30μm, spacing between lines: 50μm, number of turns: 13)

cannot be used due to the long wavelengths at these low (compared to microwave) frequencies. In these frequency ranges, lumped inductive elements are needed to fulfill analog circuit needs and other uses. There has been much investigation of spiral type magnetic inductors for these applications. Recently we have combined surface micromachining with multilevel metal interconnections to create solenoid coils suspended over the substrate on which they are fabricated, analogously to the air-bridge structures which are used to support spiral coils in some microwave circuit approaches to improve the frequency characteristics of the inductors. The use of solenoid coils is expected to achieve better magnetic flux confinement than the traditional spiral coil, at the expense of increased fabrication complexity. Figure 7 shows an SEM photomicrograph of such a suspended structure. The coil windings are seen suspended above the substrate by means of support posts. The structure is approximately 500x500 microns in area and is suspended 20-30 microns from the surface. The inductance of this structure is in the tens of nH range and the Q-factor is approximately 20 at 1-2 GHz.

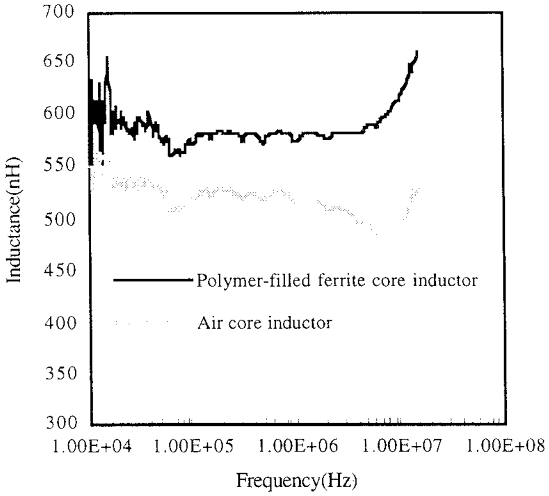

Fig. 5. Comparison of inductance of two layer spiral type inductors with and without composite material (width of conductor line: 30μm, spacing between lines: 30μm, number of turns: 16)

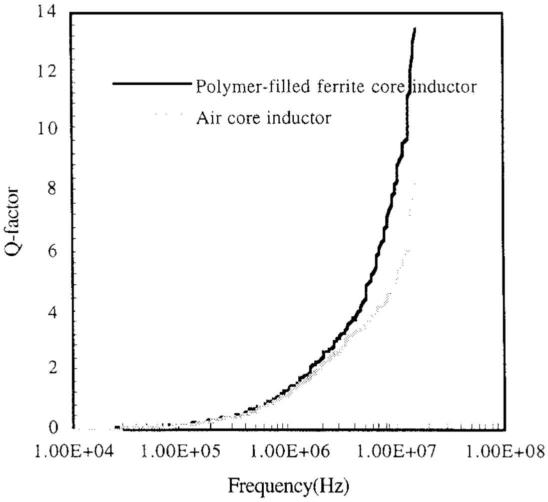

Fig. 6. Comparison of quality factor of two layer spiral type inductors with and without composite material (width of conductor line: 30μm, spacing between lines: 30μm, number of turns: 16)

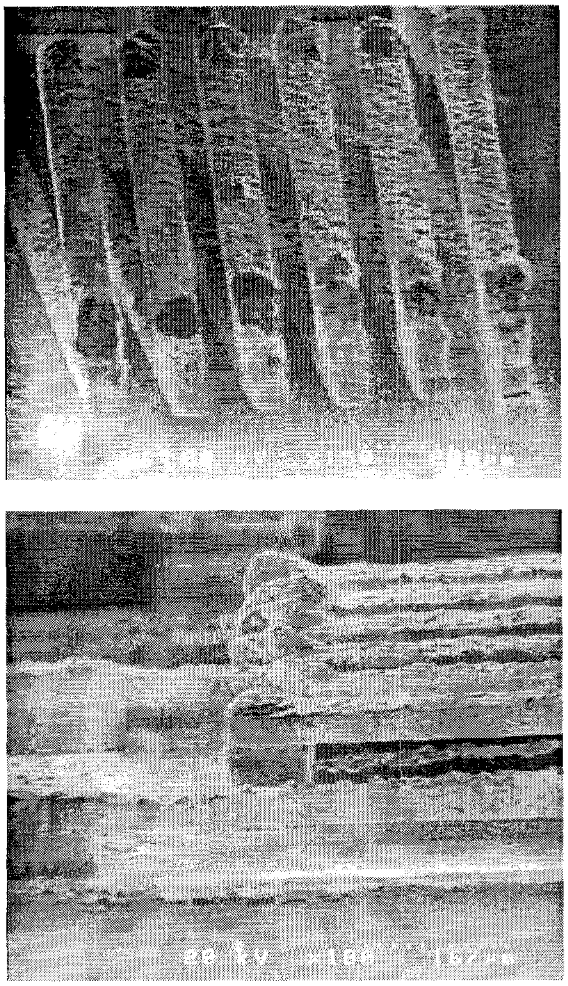

Fig. 7. Scanning electron micrographs of of surface micromachined solenoid inductor. The upper photograph is a top view and the lower photograph is a side view.

Conclusions

The next generation of low cost packages will require integrated passive components fabricated using low temperature processes. By using micromachining techniques, integrated inductors can be fabricated using low temperature processes with inductances and current carrying capabilities suitable for low power DC/DC conversion, high frequency analog circuitry, and other applications.

Acknowledgements

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