Integrated Inductors for Low Cost Electronic Packages

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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 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 Figure 1 [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 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.

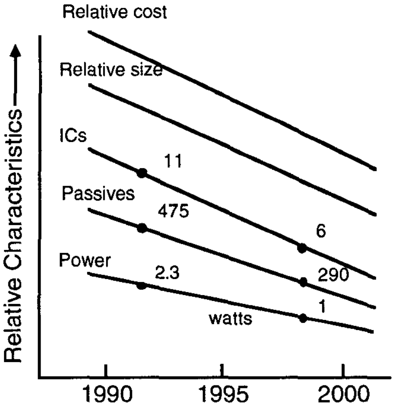

Figure 1. Components trend in camcorders (after Hitachi [1])

There has been much work in realizing integrated passives in both MCM-C (ceramic-based) and MCM-D (deposited) strategies [2-15]. 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)

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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 Inductors

In recent years, new micromachining techniques have revolutionized the conventional concept of microstructure fabrication. These micromachining techniques provide several approaches for miniaturization of magnetic power components operated at high frequencies. Cores and conductors of several tens to hundreds of microns in thickness and width with good sidewalls and dimensional control can be easily fabricated. This paper will describe the application of micromachining methods to the realization of both relatively high current 'power' inductors as well as relatively low power, high frequency 'signal' inductors. Each of these is described in some detail below.

A. Integrated Power Inductors

By introducing an electroplated nickel / iron (Ni (81%) /Fe (19%)) permalloy or other materials as a magnetic core, low temperature fabrication of power inductors is possible. The thin film nature of the core reduces eddy current losses; alternatively, the fabrication technique used is compatible with integrated laminations. Thus, hysteresis losses in cores which is a major concern in higher frequencies may be controlled. Two types of inductive components with closed magnetic circuits, the bar-type inductor and the meander-type inductor, have been fabricated at Georgia Tech. In particular, emphasis is placed on low temperature MCM-L compatible fabrication, and high current carrying capacity of the fabricated inductive component.

In the conventional toroidal inductor, conductor wires wrapped around closed magnetic cores result in low leakage flux. Such 'bar-type' inductors (the core is in the form of a bar) have been fabricated [16] using multilevel metal schemes to 'wrap' a wire around a magnetic core or air core. A section of the inductor structure is depicted in Fig. 2, and a transformer (two windings around the same core) is depicted in Fig. 3. A feature of this inductor is that a closed magnetic circuit is achieved, minimizing the leakage flux and electromagnetic interference, and increasing the inductance value and the Q-factor. Since these devices may carry significant currents, particular efforts have been made to minimize the coil resistance by increasing the thickness of the conductor lines and using electroplated vias.

A typical fabrication process starts with an oxidized (0.6 μm) 2-inch <100> silicon wafer as a substrate and polyimide as a dielectric material, although the process is completely MCM-L compatible by selecting other lower temperature organic dielectrics. Onto this substrate, chromium (500 Å) / copper (2000 Å) / chromium (700 Å) layers were deposited using electron-beam evaporation to form an electroplating seed layer. This seed layer was patterned to form a conductor network to be removed after serving as the seed layer for the conductor plating. Polyimide (Dupont PI-2611) was then spun on the wafer to build electroplating molds for the bottom magnetic cores and cured, yielding an after-cure thickness of 40 μm. Holes which contained lower conductor lines of 40 μm thickness were etched in this polyimide until the chrome/copper/chrome seed layer was exposed. The copper conductors were plated through the defined molds using standard electroplating techniques. A second polyimide layer was multi-spincoated and cured to construct a cavity of 40 μm in depth to contain a magnetic core bar and dry-etched into the bar pattern. A second seed layer was deposited and nickel (81%)/iron (19%) permalloy was then electroplated into this mold. Upon completion of the electroplating, the seed layer was selectively removed in a wet etch. A third polyimide was deposited to insulate the conductor lines and to replanarize the surface Via holes were then dry-etched through the polyimide layer, plating contact was then made to the seed layer of the lower conductors, and the metal vias were filled with plated copper. The upper conductor lines were plated through photoresist-defined molds using the same plating conditions described above. To remove the underlying seed layer, the dielectric was dry etched to the bottom and the seed layer was selectively wet etched. Figure 2 shows a scanning electron micrograph of the fully fabricated device. In this device, a 25 μm thick nickel-iron permalloy magnetic core is wrapped with 30 μm thick multilevel copper conductor lines. For an inductor size of 4 mm x 1.0 mm x 110 μm thickness having 33 turns of multilevel coils, the achieved inductance was approximately 30 nH/mm^2 at a frequency of approximately 1 MHz, corresponding to a core permeability of approximately 800. The width of conductor line and bar-core of this inductor are 80 μm and 300 μm respectively. The variation of the inductance with frequency is shown in Fig. 4. The measured DC resistance of the conductor line was approximately 0.3 ohms. The stray capacitance of the inductor was derived from the measured impedance and phase as a function of frequency using equivalent circuit analysis. From this analysis, the stray capacitance was shown to be in the several tens of pF region. The effect of the inductance falloff at higher frequencies shown in Fig. 4 is due to both the dependence of the permeability of the iron-nickel core on frequency and the effect of the stray capacitance. The maximum steady DC current which can be achieved in the bar-type inductor shown above is 2.5A, which gives a maximum allowable current density of 1×10^5 A/cm^2.

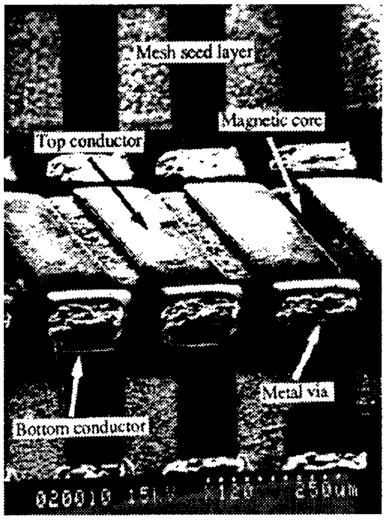

Figure 2. Scanning electron micrograph of portion of bar-type inductor.

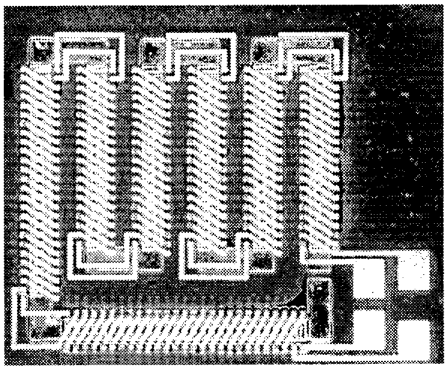

Figure 3. Optical micrograph of transformer structure.

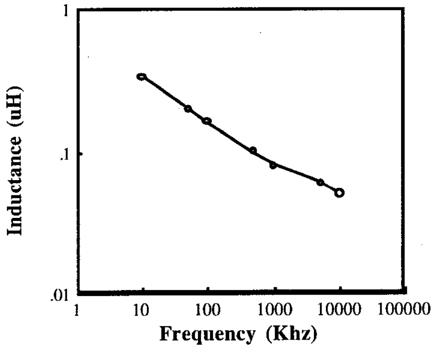

Figure 4. Typical measured inductance (by LCZ meter) vs. frequency plot of integrated inductor.

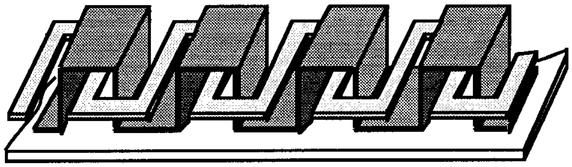

Figure 5. Meander inductor geometry, in which a magnetic core is wrapped around a planar coil.

By interchanging the roles of the conductor and magnetic core in the bar-type inductor, i.e., by wrapping a magnetic core around a planar conductor, an analogous inductive structure can be achieved. A schematic drawing of a section of this structure, the so-called 'meander' geometry, is shown in Fig. 5. [17]

This meander geometry has an advantage over the bar-type geometry in that there are no electrical vias that add resistance to the conductor coil, since the conductor is located in a single plane. A disadvantage of the meander geometry is that the total length of magnetic core (and therefore the core reluctance) is approximately 5% longer than the core length of an analogous bar-type inductor. These devices have also been fabricated at Georgia Tech, and show similar performance to the bar-type devices. The fabrication process is similar to that shown for the bar-type inductor, except that the roles of coil and core have been replaced. For typical inductor sizes of 4 mm x 1.0 mm x 130 µm, i.e. the same inductor area as the bar-type, with a 30-turn coil, similar results to the bar-type device have been realized. At a frequency of 1 Mhz, a specific inductance of 35 nH/mm^2 was achieved. In this integrated inductor, the maximum current flowing through the conductor was measured as 2 A, which gives an attainable maximum current density of 5x10^5 A/cm^2. In both inductors, quality factors of 1-2 were attained at 1 MHz. Both of these inductors have been successfully used as flyback inductors in boost DC/DC converters in voltage doubler applications [18].

B. Integrated High Frequency Inductors

In addition to the power 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) cannot be used due to the long wavelengths at these frequencies. In these frequency ranges, lumped inductive elements are needed to fulfill analog circuit needs and other uses. As MCM fabrication is inherently a multilevel process, advantages can be expected by fabricating inductors which have windings extending through several layers of the conductor/dielectric structure. It is not expected that the fabrication of these types of inductors would require any extra processing steps over those necessary to form the multichip conductors themselves, since no magnetic core will be required in many of these devices.

There has been much investigation of spiral type magnetic inductors for these applications. In this work, several types of integrated three-dimensional inductors are being investigated, each with different advantages over current planar inductors. Some allow the achievement of higher inductances; some allow quasi-distributed windings, and some allow greater magnetic coupling between inductors (e.g., transformers). The simplest of these structures is to fabricate bar-type inductors on insulating substrates and without magnetic cores. The fabrication sequence for these devices is identical to the power devices, but without the core deposition and patterning steps.

Figure 6 shows a fabricated 1mm x 4mm device on an insulating (ceramic) substrate. It should be re-emphasized that although this prototype was fabricated on ceramic, these same techniques can be used for fabrication on polymeric substrates. Figure 7 shows the measured data from this inductor. inductances in the tens of nH range and Q-factors on the order of 10 at 1 GHz. These numbers achieved with entirely unoptimized designs indicate that realizing even higher Q-factors and inductances

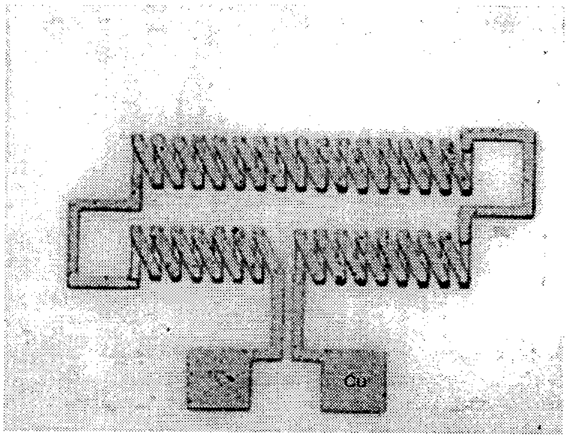

Figure 6. Air-core inductor for high frequency applications.

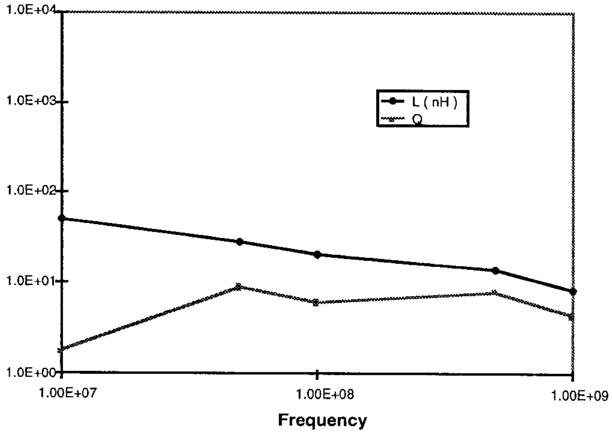

Figure 7. Measured inductance (top line) and Q-factor (bottom line) of air-core inductor as a function of frequency. Both inductance and Q-factor use the left hand scale.

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.

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References

[1] Furihata, M., Trends of the semiconductor technology and its application to visual systems, *Hitachi Review* vol.41, no.2 p.59-64, May 1992

[2] Smit, M.C.; Ferreira, J.A.; van Wyk, J.D., A planar integrated resonant LCT circuit using ceramic dielectric and magnetics, IAS '94. *Conference Record of the 1994 Industry Applications Conference Twenty-Ninth IAS Annual Meeting*, p.1233-9 vol.2, 1994

[3] Smit, M.C.; Ferreira, J.A.; van Wyk, J.D.; Holm, M.F.K., An integrated resonant DC-link converter, using planarceramic capacitor technology, *25th Annual IEEE Power Electronics, Specialists Conference*, p.664-70 vol.1, 1994

[4] Frye, R.C.; Tai, K.L.; Lau, M.Y.; Lin, A.W.C., Low-cost silicon-on-silicon MCMs with integrated passive components, *Proceedings of the 1992 International Electronics Packaging Conference*, p.343 vol.1 1992

[5] Brown, R.L.; Shapiro, A.A.; Polinski, P.W., The integration of passive components into MCMs using advanced low-temperature cofired ceramics, *International Journal of Microcircuits and Electronic Packaging* vol.16, no.4, p.328-38, 1993

[6] McCaffrey, P.J., Integrated passive components for silicon hybrid multichip modules, *Proceedings of International Electronics Packaging Conference* p.411-20 1990

[7] Love, G.R. A new multilayer process for integrated passive devices, *Elektor Electron.*, vol.14, no.155, p.14-15, April 1988

[8] Sea Fue Wang; Dougherty, J.P.; Huebner, W.; Pepin, J.G. Silver-palladium thick-film conductors, *Journal of the American Ceramic Society*, vol.77, no.12, p.3051-72, 1994

[9] Chinoy, P.B.; Tajadod, J., Processing and microwave characterization of multilevel interconnects using benzocyclobutene dielectric, *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, vol.16, no.7, p.714-19, Nov. 1993

[10] Baringer, W.B.; Brodersen, R.W., MCMs for portable applications, *Proceedings 1993 IEEE Multi-Chip Module Conference MCMC-93*, p.1-5, 1993

[11] Arnold, R.G.; Pedder, D.J., Microwave characterisation of microstrip lines and spiral inductors in MCM-D, 1992 Proceedings. *42nd Electronic Components and Technology Conference*, p.823-9, 1992

[12] Keizer, P.H.M., Ceramic multicomponent modules: A new approach to miniaturisation, *7th European Passive Components Symposium. CARTS - EUROPE '93* p.105-10

[13] Vesudevan, S.; Shaikh, A., Shrinkage matched cofireable thick film resistors for LTCC, *1994 Proceedings. 44th Electronic Components and Technology Conference*, p.612-16, 1994

[14] Dimos, D.; Lockwood, S.J.; Schwartz, R.W.; Rodgers, M.S., Thin-film decoupling capacitors for multi-chip modules, *1994 Proceedings. 44th Electronic Components and Technology Conference*, p.894-9, 1994

[15] Yamanaka, S.; Ihara, T.; Maeda, T.; Takikawa, T.; Yoshino, H., Applications of ceramic thin film technology to hybrid microelectronics, *Proceedings of the 1989 International Symposium on Microelectronics*, p.439-461989

[16] Ahn, C.H.; Kim, Y.J.; Allen, M.G., A fully integrated planar toroidal inductor with a micromachined nickel-iron magnetic bar, *IEEE Transactions on Components, Packaging, and Manufacturing Technology*, Part A, vol.17, no.3, p.463-9, Sept. 1994

[17] Ahn, C.H.; Allen, M.G., A new toroidal-meander type integrated inductor with a multilevel meander magnetic core, *IEEE Transactions on Magnetics*, vol.30, no.1, p.73-9, Jan. 1994

[18] Ahn, C.H.; Allen, M.G., A comparison of two micromachined inductors (bar-type and meander-type) for fully integrated boost DC/DC power converter, *APEC '94. Ninth Annual Applied Power Electronics Conference*, p.10-16 vol.1, 1994