High-Quality Integrated Inductors Based on Multilayered Meta-Conductors

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***Abstract*—We demonstrate high-quality integrated inductors built from a multilayer of alternating copper and ferromagnetic films. The multilayer acts as a meta-conductor whose effective permeability becomes nearly zero at its ferromagnetic anti-resonance frequency. This leads to a suppression of the skin effect and a significant increase in the quality factor of the device. Experiments show an up to 86% increase in quality factor compared to conventional copper-based spiral inductors at high frequencies.**

***Index Terms*—Ferromagnetic resonance (FMR), inductor, magnetic thin film, quality factor, radio frequency (RF).**

I. Introduction

THREMENDOUS efforts have been made in the past two decades to develop cost effective and high quality integrated inductors [1]. The most common designs are of the spiral type and are built within the interconnection layers of an integrated circuit (IC). Yet, the maximum quality factor of these devices is limited by the losses in both the conductor and the (silicon) substrate [2]. Though substrate loss can be largely removed by a variety of techniques [3]–[6], conductor loss impedes further improvement of the quality factor.

In order to improve the performance and shrink the size of on-chip inductors, devices with thin, integrated ferromagnetic cores have been investigated in recent years [7]–[10]. Although the resulting enhancement in magnetic flux increases their inductance per unit area, these devices suffer from a low ferromagnetic resonant (*FMR*) frequency, magnetic precession loss, and pronounced eddy current loss [11], [12]. For instance, a more than 10-fold enhancement of inductance was achieved at 1.0 GHz for solenoid inductors, but at the expense of a highly deteriorated quality factor [7]. Developing IC-compatible magnetic materials with high permeability, high ferromagnetic resonance frequency, and low loss still imposes a formidable challenge.

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Instead of enhancing the magnetic flux [7]–[10], thin ferromagnetic films were recently proposed as a means for reducing the conductor loss. At radio frequencies (RF), the loss in a conductor is governed by its conductivity σ and the skin depth. The conductivity of copper (Cu), the metal of choice in today's integrated electronics, is only $\sim 5\%$ lower than that of silver, the best natural conductor at room-temperature. However, at high frequencies, the electric current only flows near the conductor surface within a depth equal to the skin-depth ($< 1~\mu\mathrm{m}$ in Cu beyond 5 GHz). The result is a significant increase in the overall metal resistance which cannot be overcome by using thick conductors.

It was shown in [13] that the skin-effect may be suppressed in an artificial conductor built from a stack of alternating metallic and ferromagnetic thin films at *RF*. This is due to the fact that this artificial bi-layered meta-conductor (*ABMC*) exhibits a near zero average permeability at its effective anti-resonance frequency which may be "tuned" by properly tailoring the ratio between the thicknesses of the metallic and ferromagnetic layers. The application of such meta-conductors to transmission lines has already been shown to significantly reduce the overall loss [14], [15]. In this work we present integrated inductors built from these meta-conductors. We demonstrate an up to 86% enhancement of quality factor compared to copper based devices at 15.0 GHz.

II. Experiments

The inductors were implemented on top of a low-loss Schott AF45 glass wafer (Fig. 1). To accommodate the stress/strain, the glass wafer was coated by a thin bisbenzocyclobutene (BCB) polymer layer prior to the metal deposition. The multi-layer conductor was deposited on the top of the BCB as a stack comprising twelve periods of alternating Permalloy ($Ni_{80}Fe_{20}$) and Cu layers. The thickness of the $Ni_{80}Fe_{20}$ and Cu layers was $t_{\mathrm{NiFe}} = 40~\mathrm{nm}$, $t_{\mathrm{Cu}} = 650~\mathrm{nm}$, respectively. A number of single turn spiral inductors were fabricated with different values of geometrical width (W), length (L), and metal line-width (d) (Table I).

The reason for designing single-turn inductor was to simplify the fabrication process by eliminating the extra metal layer (and lithography mask) needed to build the bridge to connect to the inner terminal of a multi-turn coil. Moreover, proper working of the meta-conductor is only ensured if the magnetization of the $Ni_{80}Fe_{20}$ layers is saturated along the coil lines [14], [15]. In order to avoid the use of externally applied dc magnetic fields which are highly impractical for on-chip applications, one has to exploit the intrinsic and shape anisotropies of the magnetic layers. To enhance the shape anisotropy of the magnetic stripes

TABLE I
INDUCTOR DESIGN PARAMETERS WITH: WIDTH (W), LENGTH (L), COIL LINE WIDTH (D)

	Ind_12	Ind_13	Ind_14	Ind_23	Ind_24	Ind_32	Ind_33	Ind_34	Ind_42	Ind_43	Ind_44
W (μm)	300	300	300	300	300	400	400	400	200	200	200
L (μm)	600	600	600	1200	1200	800	800	800	1600	1600	1600
d (μm)	20	30	40	30	40	20	30	40	20	30	40

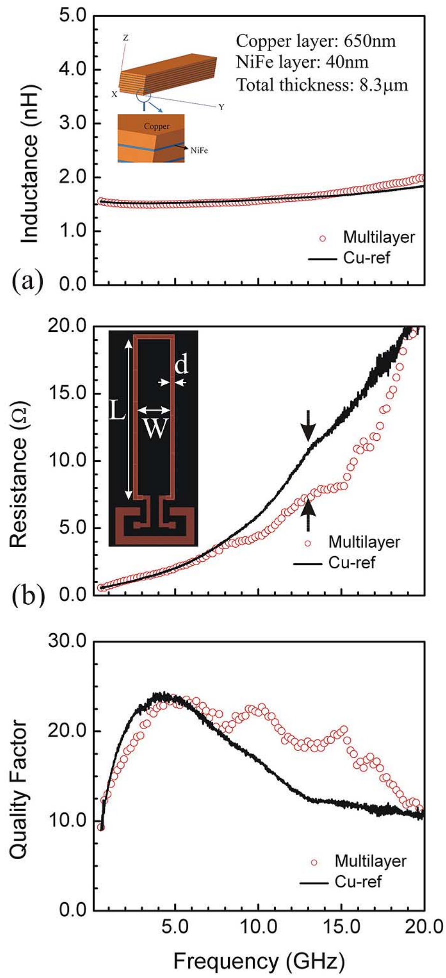

Fig. 1. Comparison of inductance, resistance, and quality factor versus frequency of a single turn *ABMC* inductor (Ind_33) and its copper counterpart. The insert in (a) shows the sketch of the *ABMC* consisting of 12 periods of bi-layered $Ni_{80}Fe_{20}(40\ \mathrm{nm})/Cu(650\ \mathrm{nm})$ stack on a glass substrate, and in (b) shows the sketch of a single turn inductor.

comprising the mutli-layer, the values d in Table I are much smaller than L and W.

For comparison, control devices built from copper were fabricated with the same configurations. The RF characterization was carried out on an Agilent PNA-L network analyzer. The pad parasitic was de-embedded from the final S-parameter data by performing a separate set of measurement on a single "through" test fixture [16], [17].

III. DISCUSSION

Fig. 1 shows the measurement results of Ind_33 (see Table I) and its copper counterpart (reference device) as an example. The *ABMC* inductor shows a lower value of resistance and a higher quality factor from 7 GHz up to 20 GHz. Near the effective anti-resonance frequency where $\mu_{NiFe} \sim -t_{\mathrm{Cu}}/t_{NiFe}$, the average permeability of the *ABMC* becomes nearly zero. This will significantly enhance skin effect suppression [13]–[15].

This reduction of metal loss is manifested by a dip in resistance and a higher quality factor (Q) compared to the reference device. However, contrary to the theoretical predictions which were verified by full-wave electromagnetic simulations, one observes a second dip in resistance (and a corresponding peak in Q) at 15GHz. To understand the origin of this phenomenon measurements were performed on a large variety of devices with various geometrical parameters, listed in Table I. It turns out that for all *ABMC* and copper devices a resistance plateau occurs at ~ 13 GHz, indicated by the arrows in Fig. 1(b). Though the exact origin of this effect is not clear yet, it is very likely caused by the tip-to-pad and pad-to-device discontinuity [18], [19]. The resistance plateau at 13 GHz gives the impression of a double resistance dip (and Q-peak). Take note that the peak in Q around 5 GHz for both *ABMC* and copper coils is related to the onset of *LC* resonance induced by the self-capacitance of the devices and is not related to the meta-conductor.

Fig. 2 compares the enhancement of the quality factors versus inductance of various inductors (Table I) at 10.0 GHz [Fig. 2(a)], 12.5 GHz [Fig. 2(b)] and 15.0 GHz [Fig. 2(c)]. Here 10.0 and 15.0 GHz are chosen to be close to the double Q-peak, and 12.5 GHz is close to the resistance plateau. Compared to the reference, an 86% increase in quality factor is obtained from Ind_13 at 15.0 GHz. Finally, we should point to the fact that the etching process leads to significant undercut ($\sim 10\mu\mathrm{m}$ measured by Atomic Force Microscopy). Were it not for such issues, we may have expected a higher quality factor of the *ABMC*-based inductors.

It is worth mentioning that reducing the conductor loss will have a much less pronounced effect on Q if the substrate loss dominates. Nonetheless, there are scenarios where meta-conductors may still be useful on normal Si substrates. Current IC process technology allows relatively thick insulating $\mathrm{SiO_2}$ layers ($\sim 10\mu$ m) to be placed in between Si and the coil metal. This will reduce substrate coupling and, therefore, substrate loss. In these circumstances using meta-conductors will still have a significant effect on Q. Moreover, the *ABMC* can be viewed as a normal conductor with a low, frequency dependent sheet resistance. Therefore, although our experiments were restricted to single turn coils, similar improvement on quality factor should be observed for multi-turn inductors.

IV. CONCLUSION

We have demonstrated high-quality integrated inductors based on *ABMC*. This artificial conductor shows a significant reduction of the ohmic loss at radio frequencies due to a suppression of the skin-effect. The technology can be implemented into the Saddle Add-on metallization [20]. We believe that

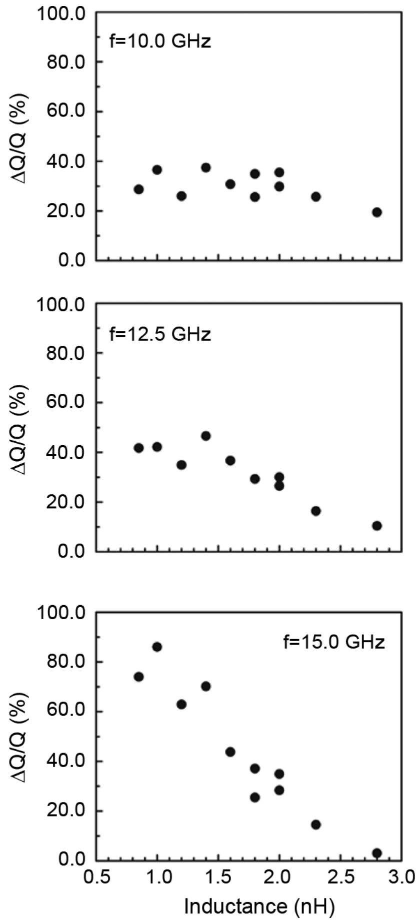

Fig. 2. Comparison of the enhancement of quality factors $\Delta Q/Q = (Q_{ABMC} - Q_{Cu})/Q_{Cu}$ versus inductance of various inductors (Table I) at (a) 10.0 GHz, (b) 12.5 GHz, and (c) 15.0 GHz.

the concept will provide a new means of further advancing high-speed electronics, and may lead to breakthroughs in the semiconductor industry.

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REFERENCES

[1] J. N. Burghartz, D. C. Edelstein, M. Soyuer, H. A. Ainspan, and K. A. Jenkins, “RF circuit design aspects of spiral inductors on silicon,” *IEEE J. Solid-State Circuits*, vol. 33, no. 12, pp. 2028–2034, Dec. 1998.

[2] J. N. Burghartz and B. Rejaei, “On the design of RF spiral inductors on silicon,” *IEEE Trans. Electron Devices*, vol. 50, no. 3, pp. 718–729, Mar. 2003.

[3] J. B. Yoon, B. K. Kim, C. H. Han, E. S. Yoon, and C. K. Kim, “Surface micromachined solenoid on-Si and on-glass inductors for RF applications,” *IEEE Electron Device lett.*, vol. 20, no. 9, pp. 487–489, Sep. 1999.

[4] C. P. Yue and S. S. Wong, “On-chip spiral inductors with patterned ground shields for Si-based RF Ics,” *IEEE J. Solid-State Circuits*, vol. 33, no. 5, pp. 743–752, May 1998.

[5] J. B. Yoon, Y. S. Choi, B. I. Kim, Y. Eo, and E. Yoon, “CMOS-compatible surface-micromachined suspended-spiral inductors for multi-GHz silicon RF ICs,” *IEEE Electron Device lett.*, vol. 23, no. 10, pp. 591–593, Oct. 2002.

[6] L. H. Guo, Q. X. Zhang, G. Q. Lo, N. Balasubramanian, and D. L. Kwong, “High-performance inductors on plastic substrate,” *IEEE Electron Device lett.*, vol. 26, no. 9, pp. 619–621, Sep. 2005.

[7] Y. Zhuang, M. Vroubel, B. Rejaei, and J. N. Burghartz, “Ferromagnetic RF inductors and transformers for standard CMOS/BiCMOS,” in *Techn. Dig. IEDM*, 2002, pp. 475–478.

[8] M. Yamaguchi, T. Kuribara, and K. I. Arai, “Two-port type ferromagnetic RF integrated inductor,” in *IEEE MTT-S Int. Dig.*, 2002, pp. 197–200.

[9] V. Korenivski and R. B. Dover, “Design of high frequency inductors based on magnetic films,” *IEEE Trans. Magnetics*, vol. 34, no. 4, pp. 1375–1377, Jul. 1998.

[10] J. Park and M. Allen, “Integrated electroplated micromachined magnetic devices using low temperature fabrication processes,” *IEEE Trans. Electron. Packag. Manufac.*, vol. 23, no. 1, pp. 48–55, Jan. 2000.

[11] T. J. Klemmer, K. A. Ellis, L. H. Chen, B. van Dover, and S. Jin, “Ultrahigh frequency permeability of sputtered FeCoB thin films,” *J. Appl. Phys.*, vol. 87, pp. 830–833, 2000.

[12] S. X. Wang, N. X. Sun, M. Yamaguchi, and S. Yabukami, “Properties of a new soft magnetic material,” *Nature*, vol. 407, pp. 150–151, 2000.

[13] B. Rejaei and M. Vroubel, “Suppression of skin-effect in metal/ferromagnet superlattice conductors,” *J. Appl. Phys.*, vol. 96, pp. 6863–6868, 2004.

[14] Y. Zhuang, B. Rejaei, H. Schellevis, M. Vroubel, and J. N. Burghartz, “Magnetic-multilayered interconnects featuring skin effect suppression,” *IEEE Electron Device lett.*, vol. 29, no. 4, pp. 319–321, Apr. 2008.

[15] I. Iramnaaz, T. Sandoval, Y. Zhuang, H. Schellevis, and B. Rejaei, “High quality factor RF inductors using low loss conductor featured with skin effect suppression for standard CMOS/BiCMOS,” in *Proc. IEEE 61st ECTC*, 2011, pp. 163–168.

[16] Y. Tretiakov, K. Vaed, D. Ahlgren, J. Rascoe, S. Venkatadri, and W. Woods, “On wafer de-embedding for SiGe/BiCMOS/RFCMOS transmission line interconnect characterization,” in *Proc. Interconnect Tech. Conf.*, 2004, pp. 166–168.

[17] E. S. Daniel, N. E. Harff, V. Sokolov, S. M. Schreiber, and B. K. Gilbert, “Network analyzer measurement de-embedding utilizing a distributed transmission matrix bisection of a single THRU structure,” in *ARFTG Conf. Dig. Spring*, 2004, pp. 61–68.

[18] J. Lim, D. Kwon, J.-S. Rieh, S.-W. Kim, and S. W. Hwang, “RF characterization and modeling of various wire bond transitions,” *IEEE Trans. Adv. Packag.*, vol. 28, no. 4, pp. 772–778, Nov. 2005.

[19] D. F. Williams, “On-wafer measurement at millimeter wave frequencies,” in *IEEE MTT-S Int. Dig.*, Jun. 1996, vol. 3, pp. 1683–1686.

[20] B. Rejaei, J. N. Burghartz, and H. Schellevis, “Saddle add-on metallization (SAM) for Rf inductor implementation in standard IC interconnects,” in *Techn. Dig. IEDM*, 2002, pp. 467–470.