Integrated Solenoid Inductors With Patterned, Sputter-Deposited $Cr/Fe_{10}Co_{90}/Cr$ Ferromagnetic Cores

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***Abstract*—Ferromagnetic (FM) films suitable for implementation in between interconnect layers of a standard CMOS fabrication process are demonstrated to yield considerable size reduction of monolithic radio frequency (RF) inductors, leading to lower cost. The deposition of a FM Cr(5 nm)/$Fe_{10}Co_{90}$(500 nm)/Cr(15 nm) stack is performed by magnetron sputtering at room temperature under a dc magnetic field of $\sim$ 10 mT along the magnetic easy-axis. A lift-off technique, using a four-layer shadow mask, is used for pattern transfer to the magnetic stack to circumvent apparent difficulties in the patterning of FM films. A series of solenoid-type inductors with FM cores are demonstrated and compared to control devices with air cores. A more than eight-fold enhancement of the inductance and a seven-fold improvement of the quality factor are achieved.**

***Index Terms*—Inductor, micropatterning, on-chip, radio frequency, shadow mask.**

I. Introduction

ON-CHIP radio frequency (RF) passive components such as inductors, transformers, and microstrips occupy excessive chip area, and thus considerably add to the cost of an integrated RF transceiver. Recently, soft ferromagnetic (FM) materials have been proposed to increase the inductance per area at RF without any considerable degradation of the quality factor (Q) [1]–[6]. Most of those materials and processes, however, are not well applicable to industrial integrated circuit (IC) processing.

Fully CMOS-compatible integration of magnetic materials is not straightforward. One of the major obstacles is the micro patterning of the magnetic films. The common pattern transfer techniques, i.e., wet chemical etching, dry etching, electroplating through a predefined mask, and the common lift-off technique are applicable only at the following restrictions: wet chemical etching usually causes an excessive and uncontrollable under-etching [7]. Dry etching, on the other hand, induces damage that affects the magnetic properties [8], [9]. Electroplating offers direct deposition of the desired FM-film pattern, but does not allow for forming a laminated FM/insulator multilayer structure to reduce eddy current effects; furthermore, most FM materials developed so far are based on sputter deposition [1], [2]. Given those concerns, the most promising approach appears to be the lift-off technique in combination with sputter-deposited FM films. The traditional solvent lift-off technique cannot be applied well because of the near-conformal sputter deposition. The shadow mask technique, used to fabricate silicon germanium (SiGe) quantum wire and dot structures [10], allows for patterning near-conformal films, but is based on process temperatures above 700 °C. Such high temperatures, however, are incompatible with aluminum (Al) metallization, which is still the dominant metallization process in semiconductor industry.

In this work, we present a novel four-layer shadow mask to pattern a sputtered Cr(5 nm)/$Fe_{10}Co_{90}$(500 nm)/Cr(15 nm) stack at low-process temperatures. Furthermore, we present FM-core, solenoid-type inductors with considerable improvements of inductance and quality factor at RF, by using a CMOS-compatible process. We believe that availability of this technique is a major step toward the introduction of FM films to RF-IC technology.

II. Fabrication and Characterization

The evolution of the solenoid structure during the process flow is shown schematically in Fig. 1(a)-(d). The process starts with the growth of a 1-μm-thick SiO_2 layer on a p-type silicon substrate. Next, a sputtered 2-μm-thick Al layer (the first metal) is structured into a series of parallel bars and covered subsequently by a 4-μm-thick SiO_2 layer. The surface is then planarized by chemical-mechanical-polishing (CMP) with a 1-μm-thick SiO_2 layer remaining on top of the Al bars. After deposition of a 0.5-μm-thick silicon carbide (SiC) etch-stop layer, a series of layers, consisting of 1.6 μm SiO_2, 3.5-μm polyimide (PI2611, Dupont), and 0.8-μm Si_3N_4, are deposited and subsequently structured as shown in Fig. 1(a). The shadow mask structure is formed by generation of a large lateral under-etching over 2 μm in the SiO_2 layer underneath the patterned Si_3N_4 and the polyimide layers (its cross-sectional view is shown in Fig. 1(e). The typical width of the shadow mask (Ws) used here is 10 μm. A multilayer magnetic-film stack, consisting of Cr(5 nm)/$Fe_{10}Co_{90}$(500 nm)/Cr(15 nm), is sputtered under a dc magnetic field of $\sim$ 10 mT along the y–axis (the easy axis) for creating the intrinsic magnetic anisotropy [Fig. 1(b)]. Due to the gap remaining after the sputter deposition [Fig. 1(b)], the shadow mask structure can easily be lifted off by immerging samples in buffered (1:7) HF

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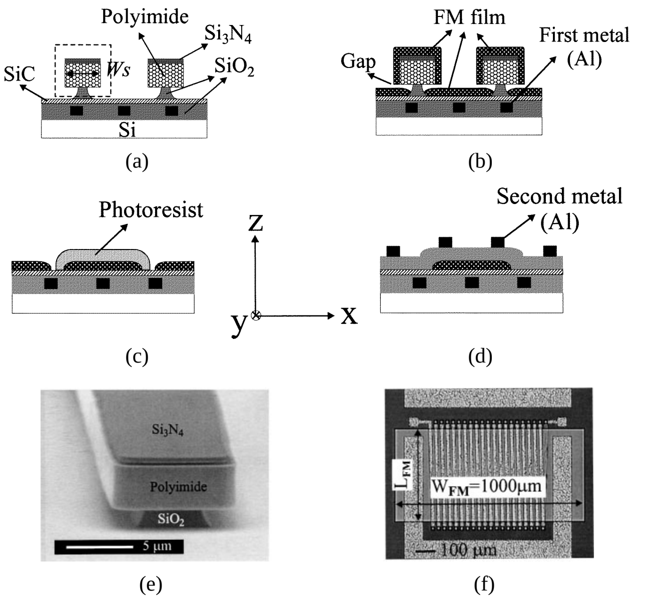

Fig. 1. Schematic cross-sectional views of the process flow (a)-(d). The shadow mask structure is outlined in (a) by the dashed line. SEM micrographs of (e) cross-sectional view of a shadow mask structure with over 2 μm lateral undercut and (f) top view of a solenoid inductor (20-turn, FM-core: 1000×500 μm^2). The Al line width and line spacing of the solenoid inductors are both 20 μm.

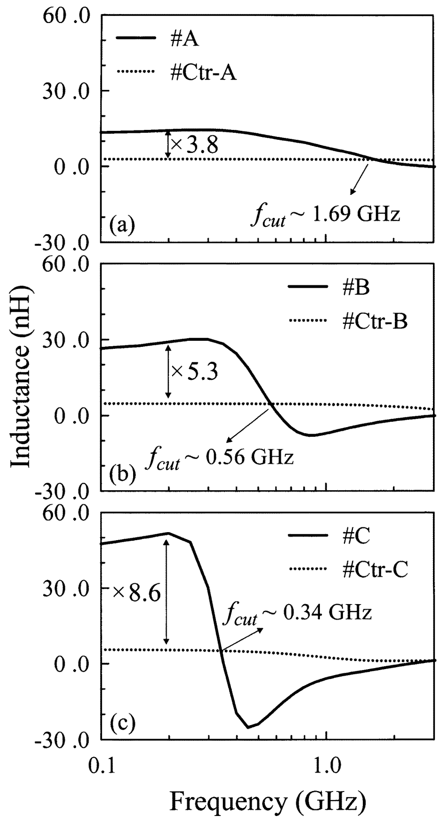

Fig. 2. Comparison of the measured inductance of (a) #A (FM core: 1000×500 μm^2) and #Ctr-A, (b) #B (FM core: 1000×500 μm^2) and # Ctr-B, (c) #C (FM core: 1000×2000 μm^2) and # Ctr-C, wersus frequencies. The $f_{\rm cut}$ denotes the cut-off frequency, which is defined as the frequency at which the enhancement of the inductance over the control device equals to zero.

solution [Fig. 1(c)]. At the end, after etching the undesired part of the Cr/$Fe_{10}Co_{90}$/Cr film in a solution of $FeCl_3$: HCl, the fabrication of the solenoid coil is completed by deposition of a 1-μm-thick SiO_2 insulation layer, plasma etching of SiO_2(1 μm)/SiC(0.5 μm)/SiO_2(1 μm) to open the contact holes, sputtering, and structuring the second metal layer (3-μm-thick Al) to connect to the first metal layer [Fig. 1(d)].

III. Results and Discussion

A saturation magnetization of 1.63 ($\pm 5\%$)T was measured for the Cr/$Fe_{10}Co_{90}$/Cr films by using vibrating sample magnetometry (VSM). The feature of the frequency dependence of the permeability is similar as described in [1] and [2] and the references therein. Electrical device characterization was performed by using a HP-8510 network analyzer. Three 20-turn solenoidal inductors (#A, #B, and #C) with identical Al line width (20 μm), Al line spacing (20 μm), and Cr/$Fe_{10}Co_{90}$/Cr core width ($W_{FM} = 1000$ μm) were fabricated and shown in Fig. 1(f) (#A). The Cr/$Fe_{10}Co_{90}$/Cr core length (L_{FM}) were 500, 1000, and 2000 μm for #A, #B, and #C, respectively. For comparison, a 0.5-μm-thick, and 500-, 1000-, and 2000-μm-long SiO_2 dummy layer has been used to replace the Cr/$Fe_{10}Co_{90}$/Cr core in the control devices #Ctr-A, #Ctr-B, and #Ctr-C, respectively. At comparably low frequencies, the inductance of #A, #B, and #C has been enhanced by insertion of the Cr/$Fe_{10}Co_{90}$/Cr core (Fig. 2). Compared to the control devices, over eight-fold enhancement of inductance has been found for #C at 0.2 GHz. The enhancement of inductance becomes gradually higher with increasing the $L_{\rm FM}$. Due to the increase of negative mutual inductance between the first and second metal layers by increasing the length of the dummy SiO_2 core from 500 (#Ctr-A) to 2000 μm (#Ctr-C), the enhancement of inductance is limited. On the other hand, by insertion of the Cr/$Fe_{10}Co_{90}$/Cr core, the inductance of #A, #B, and #C is predominately caused by the high permeability of the FM core as long as the operating frequency is far below the FM resonance (FMR) frequency and the skin depth is much larger than the core's thickness. The impact of the negative mutual inductance then becomes a minor issue. Consequently, a larger enhancement of the inductance has been obtained for devices with a longer L_{FM}.

At high frequency, the inductance of #A, #B, and #C is degraded by mainly three effects; 1) the electromagnetic resonance, i.e., *LC* resonance, 2) the FMR of the FM core, and 3) the decrease of the effective permeability of the FM core result from the eddy current effect. The cut-off frequency $f_{\rm cut}$ shown in Fig. 2 is defined as the frequency at which the enhancement of the inductance over the control device equals to zero. The dependence of $f_{\rm cut}$ on L_{FM} (#A, #B, and #C) indicates that the $f_{\rm cut}$ is predominately determined by the electromagnetic resonance and is traded against the enhancement in inductance (Fig. 2). From results on electroplated FM devices we have seen that a FM inductor can be optimized by tailoring the coil structure and the shape of the FM film [6]. Compared to the control devices, the enhancement of the quality factors of solenoids with FM cores is shown in Fig. 3. The quality factors benefit from the increase of the inductance with insertion of the FM cores at low frequencies. They are deteriorated at high frequencies, however, due to the eddy current and FMR losses in the Cr/$Fe_{10}Co_{90}$/Cr cores.

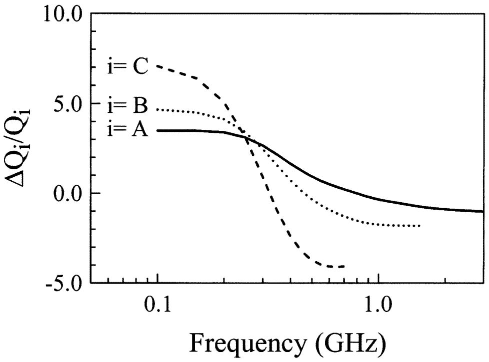

Fig. 3. Enhancement of the quality factors of #A, #B, and #C compared to their control devices # Ctr-A, # Ctr-B, and # Ctr-C, respectively. $\Delta Q_i = Q_i - Q_{\mathrm{Ctr}-i}$, $i = A, B, C$.

IV. Conclusions

Patterning of Cr/$Fe_{10}Co_{90}$/Cr films imbedded into the core of a solenoid inductor has been realized on a Si substrate by using a CMOS-compatible fabrication process. A novel lift-off technique, using a four-layer shadow mask, has allowed for patterning of the sputtered FM film at low temperatures. More than eight-fold enhancement in inductance and seven-fold improvement in quality factor have been obtained.

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