Briefs

A High-Performance Micromachined RF Monolithic Transformer With Optimized Pattern Ground Shields (OPGS) for UWB RFIC Applications

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Abstract—In this brief, we demonstrate that high-quality-factor and low-power-loss transformers can be obtained if the optimized pattern ground shields (OPGS) of polysilicon is adopted and the CMOS process-compatible backside inductively coupled-plasma (ICP) deep-trench technology is used to selectively remove the silicon underneath the transformers completely. OPGS means that the redundant PGS of a traditional complete PGS, which is right below the spiral metal lines of the transformer, is removed for the purpose of reducing the large parasitic capacitance. The results show that, if the OPGS was adopted and the backside ICP etching was done, a 69.3% and a 253.6% increase in quality factor, a 10.5% and a 14% increase in magnetic-coupling factor (k_{Im}), a 17.2% and a 51.1% increase in maximum available power gain (G_{Amax}), and a 0.682- and a 1.79-dB reduction in minimum noise factor (NF_{min}) were achieved at 5 and 8 GHz, respectively, for a bifilar transformer with an overall dimension of $230 \times 215 \mu m^2$.

Index Terms—Micromachined, optimized pattern ground shield (OPGS), power gain, quality-factor, radio frequency integrated circuits (RFICs), transformer.

I. INTRODUCTION

The minimum noise figure NF_{min} of a transformer (i.e., $10 \cdot \log(1/G_{Amax})$), in which G_{Amax} is the maximum available power gain [1], is a direct index of the power loss (in decibels) of the device. In the design of low-voltage and high-performance CMOS (or BiCMOS) radio frequency integrated circuits (RFICs) [2]–[4], the quality factor (Q -factor) and NF_{min} performances of the transformers used are crucial for the phase-noise performance of the voltage-controlled oscillators and the noise figure performance of the low-noise amplifiers. However, the Q -factor and NF_{min} performances of RF transformers fabricated on normal silicon substrates are normally not satisfactory mainly due to their capacitive and electromagnetic coupling with the silicon substrate. Adding polysilicon (or metal) pattern ground shields (PGS) underneath the transformers (or inductors) has been widely adopted to suppress the electromagnetic-coupling-induced loss (or eddy-current loss) in the silicon substrate [5], [6], so the maximum Q -factor of the devices can be improved. However, the large parasitic capacitance between the PGS and the devices leads to poorer Q -factor in high-frequency and lower self-resonant frequency (f_{SR}). Fortunately, this problem can be improved by our proposed optimized PGS (OPGS). OPGS means that the redundant PGS of a traditional complete PGS, which is right below the spiral metal lines of an

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Fig. 1. (a) Top-view die photo of a bifilar transformer with metal width of $10 \mu m$, coil spacing (between the primary and the secondary coil) of $2 \mu m$, inner dimension of $62 \times 73 \mu m$, and overall dimension of $230 \times 215 \mu m$. (b) Schematic diagrams of the proposed OPGS formed by the N^+ polysilicon layer, and a corresponding traditional complete PGS (STD PGS) for comparison.

RF-passive device, is removed for the purpose of reducing the large parasitic capacitance [see Fig. 1(b)].

NF_{min} (or G_{Amax}) of a transformer is a function of its Q -factors (Q_1 and Q_2), magnetic-coupling factor (k_{Im}), and resistive-coupling factor (k_{Re}) [6], [7]. In this brief, we demonstrate that the NF_{min} (or G_{Amax}) performance of a transformer can be optimized if the combination of OPGS (mainly for improving k_{Im}) and CMOS-compatible backside inductively coupled-plasma (ICP) deep-trench technology (mainly for improving Q_1 and Q_2) is adopted.

II. TRANSFORMER AND OPGS STRUCTURE

Fig. 1(a) shows the top-view die photo of a symmetrical bifilar transformer, which has turn numbers of three, metal width of $10 \mu m$, coil spacing of $2 \mu m$, inner dimension of $62 \times 73 \mu m$, and overall dimension of $230 \times 215 \mu m$. Port-1 and Port-2 stand for the input port and the output port of the network analyzer, respectively. The transformers under study were fabricated with a $0.35 \mu m$ SiGe BiCMOS technology on a p-type silicon substrate with thickness of $318 \mu m$ and resistivity of $10 \Omega \cdot cm$. The main features of the back-end processes are as follows. There were three metal layers, named M1–M3 from bottom to top. The thickness of M3 was $3.05 \mu m$, and that of M1 and M2 were $0.665 \mu m$. The oxide thickness was $1 \mu m$ between adjacent metal layers, and $1.1 \mu m$ between M1 and the silicon substrate. Fig. 1(b) shows the schematic of the proposed OPGS formed by the N^+ polysilicon layer with thickness of $0.28 \mu m$ and sheet resistance of $102 \pm 15.3 \Omega/sq$. The width (X) and slot (Y) were 4 and

Fig. 2. (a) Process steps of the backside ICP deep-trench etching technology. (b) Backside die photos of the transformer without OPGS after the backside ICP etching (ICP TF), and the transformer with OPGS after the backside ICP etching (OPGS-ICP TF).

1 μm , respectively. To minimize the voltage variation in the OPGS, an M1 pattern in the shape of a cross, which connects the polysilicon layer via contacts, had been added. What is also shown in Fig. 1(b) is the schematic of a corresponding traditional complete PGS (STD PGS) for comparison.

III. DEEP-TRENCH TECHNOLOGY

The processing steps of our CMOS-compatible backside ICP deep-trench technology are shown in Fig. 2(a) and described as follows. First, for the ease of chip handling, the front side of the die ($\sim 5 \times 5 \text{ mm}$) with transformers was stuck to a glass substrate. Note that this process step can be omitted when applied in mass production, because the wafer diameter is large. After standard photolithography processes on the backside of the die, the ICP etching was used to remove the silicon underneath the transformers. Specifically, the silicon below the rectangular area surrounded by the dash line as indicated in Fig. 1(a) was fully dry-etched away. The main gases used during the ICP-etching process were alternate SF_6 (for etching) and C_4F_8 (for passivation) with a 17-s cycle. Finally, the adhesive and photoresist, which covered the front-side and backside of the die, respectively, were removed for test purpose. Compared with the traditional backside wet bulk micromachining in [8], the dry ICP etching has the advantages of forming vertical sidewalls and being

Fig. 3. Simplified small-signal equivalent-circuit model of a monolithic RF transformer. Expressions of $G_{A \max}$, Q_1 , Q_2 , k_{Re} , and k_{Im} are also shown.

fully CMOS process compatible since it is a standard processing technique in modern CMOS technology.

The ICP-etching rate of silicon and oxide were about 2 and 0.02 $\mu\text{m}/\text{min}$, respectively. That is, silicon to oxide ICP-etch selectivity was about 100. Since the ratio between the silicon substrate thickness (318 μm) and the oxide thickness underneath M1 layer (1.1 μm) was high (≈ 289.1), in this brief, we precisely control the etching time (159 min) to fully remove silicon while keeping oxide underneath M1 layer nearly intact. Another feasible approach is to thin down the silicon substrate to about 100 μm by mechanical lapping [9] before the ICP-etching postprocess. Since the ICP-etching time was shortened from 159 to 50 min, the process margin (of keeping oxide underneath M1 layer nearly intact) has been improved.

Fig. 2(b) shows the backside die photos of the transformer without OPGS after the backside ICP etching (ICP TF) and the transformer with OPGS after the backside ICP etching (OPGS-ICP TF). The exposed front-side on-chip transformer and PGS were visible to the naked eye. This means the silicon underneath the transformers is indeed nearly fully dry-etched away.

IV. RESULTS AND DISCUSSIONS

The S -parameter measurements were performed from 0.1 to 20 GHz by an HP-8510C vector network analyzer. Fig. 3(a) shows the complete small-signal equivalent-circuit model of a transformer on a silicon substrate [10], which can be simplified to the one shown in Fig. 3(b). Based on the simplified transformer model in Fig. 3(b), it is convenient to use the Z -parameters Z_{ij} ($i, j = 1, 2$) to characterize the electrical properties of a transformer [6]. Z_{11} ($= R_{s1-\text{eff}} + j\omega L_{s1-\text{eff}}$) and Z_{22} ($= R_{s2-\text{eff}} + j\omega L_{s2-\text{eff}}$) represent the equivalent single-port (i.e., one port is short with the other coil open) input impedance of the primary and the secondary coil inductor, respectively, of the transformer. $Z_{12} = Z_{21}$ ($= R_M + j\omega L_M$) represents the mutual impedance of the transformer. That is, $L_{s1-\text{eff}}$, $L_{s2-\text{eff}}$, and L_M represent the primary, secondary, and mutual inductances, respectively, and $R_{s1-\text{eff}}$, $R_{s2-\text{eff}}$, and R_M represent the primary, secondary, and mutual resistances, respectively, of the transformer. What is also shown in Fig. 3(b) are the expressions of the $G_{A \max}$, Q -factors of the primary coil (Q_1) and the secondary coil (Q_2), k_{Im} , and k_{Re} of a transformer

TABLE I
DETAILED COMPARISONS OF THE EXTRACTED PARAMETERS OF A SET OF BIFILAR TRANSFORMERS
WITH THE SAME LAYOUT BUT DIFFERENT PGS STRUCTURES

PGS structure	Transformer structure	Overall dimension (μm^2)	Inner dimension (μm^2)	Technology	f_{SR} (GHz)	Frequency (GHz)	Q_1	Q_2	k_{Im}	k_{Re}	G_{Amax}
No PGS (STD TF)	Bifilar (on 318 μm -thick normal Si substrate)	230×215	62×73	0.35 μm SiGe BiCMOS	15.6	2.4	6.48	6.71	0.70	0.39	0.64
						4.2	6.12	7.14	0.69	0.49	0.67
						5.2	5.55	6.63	0.69	0.52	0.66
STD PGS (N^+ imp.) (PGS TF)					10.1	2.4	6.23	6.44	0.80	0.51	0.68
						4.2	6.94	7.77	0.82	0.61	0.75
						5.2	6.59	7.97	0.83	0.68	0.77
STD PGS (P^+ imp.)					10	2.4	6.30	6.41	0.80	0.51	0.68
						4.2	7.06	7.53	0.82	0.62	0.75
						5.2	6.75	7.42	0.84	0.69	0.77
OPGS (N^+ imp.) (OPGS TF)					11.1	2.4	7.85	7.92	0.80	0.42	0.72
						4.2	9.58	10.60	0.82	0.49	0.79
						5.2	8.64	10.10	0.83	0.60	0.80

TABLE II
EXTRACTED SMALL-SIGNAL EQUIVALENT-CIRCUIT PARAMETERS OF STD TF (WITHOUT PGS), PGS TF (WITH STD PGS), OPGS TF (WITH OPGS), ICP TF (WITHOUT PGS), AND OPGS-ICP TF (WITH OPGS)

Technology	TSMC 0.35 μm SiGe BiCMOS				
Transformer ID	STD TF (w/o PGS)	PGS TF (w/i STD PGS)	OPGS TF (w/i OPGS)	ICP TF (w/o PGS)	OPGS-ICP TF (w/i OPGS)
Structure	Bifilar				
Width (μm)	10				
Spacing (μm)	2				
Turn number (N)	3				
Turn ratio	1:1				
Premary coil	M6				
Secondary coil	M6				
Overall dimension (μm^2)	230×215				
Inner dimension (μm^2)	62×73				
Frequency range	DC - 15.6 GHz	DC - 11 GHz		DC - 15.6 GHz	DC - 11 GHz
$R_{s1} (\Omega)$	1.97	2.01	1.99	1.97	1.99
$L_{s1} (\text{nH})$	1.85	1.81	1.83	1.85	1.83
$C_{s1} (\text{fF})$	10	10	10	10	10
$R_{s2} (\Omega)$	1.97	2.01	1.99	1.97	1.99
$L_{s2} (\text{nH})$	1.85	1.81	1.83	1.85	1.83
$C_{s2} (\text{fF})$	10	10	10	10	10
$C_{\text{ox}1} (\text{fF})$	220	3000	225	220	225
$C_{\text{sub}1} (\text{fF})$	25	65	65	4	6
$R_{\text{sub}1} (\Omega)$	320	950	950	2400	2600
$C_{\text{ox}2} (\text{fF})$	220	3000	225	220	225
$C_{\text{sub}2} (\text{fF})$	25	65	65	4	6
$R_{\text{sub}2} (\Omega)$	320	950	950	2400	2600
k_{Im}	0.7	0.8	0.8	0.7	0.8
$C_c (\text{fF})$	10	10	10	10	10

in terms of its measured Z -parameters, which can be converted from the measured S -parameters.

Table I shows a detailed comparison of the extracted parameters of a set of bifilar transformers with the same layout but with different PGS structure. As can be seen, the transformer with OPGS is the best from the view points of Q_1 , Q_2 , G_{Amax} , and NF_{min} . Besides, the effect of the STD PGS formed by the N^+ polysilicon layer (with thickness of 0.28 μm and sheet resistance of $102 \pm 15.3 \Omega/\text{sq}$) on the

transformer is about the same as that of the STD PGS formed by the P^+ polysilicon layer (with thickness of 0.28 μm and sheet resistance of $1035 \pm 155 \Omega/\text{sq}$). The measured G_{Amax} (0.78 at 5.2 GHz) of our OPGS-ICP transformer (overall dimension of $230 \times 215 \mu\text{m}$) is better than that (0.603 at 5.2 GHz) of a transformer with dimension of $300 \times 300 \mu\text{m}$ on a quartz substrate [6] and better than that (0.764 at 5.2 GHz) of a transformer with dimension of $280 \times 280 \mu\text{m}$ on a porous silicon substrate [7].

Fig. 4. Measured (a) Q_1 , (b) k_{Im} and k_{Re} , (c) G_{Amax} , and (d) NF_{min} versus frequency characteristics of STD TF, ICP TF, and OPGS-ICP TF.

Table II shows a summary of the extracted small-signal equivalent circuit parameters of STD TF (without PGS), PGS TF (with STD PGS), OPGS TF (with OPGS), ICP TF (without PGS), and OPGS-ICP TF (with OPGS). The extracted values of C_{ox1} and C_{ox2} of the OPGS TF are lower than those of the PGS TF, since there is no polysilicon layer and gate-oxide layer directly beneath the spiral metal lines of the OPGS TF. This explains why in Table I that the OPGS TF exhibits better Q_1 , Q_2 , f_{SR1} , and f_{SR2} performances than the PGS TF.

Fig. 4(a) shows the measured Q_1 versus frequency characteristics of STD TF (i.e., without both OPGS and ICP etching), ICP TF, and OPGS-ICP TF. The result shows that, if the OPGS was adopted and the backside ICP etching was done, a 69.3% (from 5.66 to 9.58) and a 253.6% (from 3.79 to 13.4) increase in Q_1 was achieved at 5 and 8 GHz, respectively. The reason why ICP TF and OPGS-ICP TF exhibit higher Q_1 than that of STD TF is mainly attributed to the reduction of the silicon-substrate loss. In addition, in the frequency range of roughly 3–7 GHz, OPGS-ICP TF exhibited Q_1 , which was a little lower than that of ICP TF because there was an additional induced-eddy-current loss in the OPGS.

Fig. 4(b) shows the measured k_{Im} and k_{Re} versus frequency characteristics of STD TF, ICP TF, and OPGS-ICP TF. The results show that, if the OPGS was adopted and the backside ICP etching was done, a 10.5% (from 0.713 to 0.788) and a 14% (from 0.7 to 0.798) increase in k_{Im} was achieved at 5 and 8 GHz, respectively. The reason why OPGS-ICP TF exhibited higher k_{Im} (0.788 at 5 GHz) than those of STD TF (0.713 at 5 GHz) and ICP TF (0.688 at 5 GHz) was mainly attributed to the better confinement of the magnetic field achieved by the OPGS. Besides, the reason why STD TF exhibited higher

k_{Re} (0.514 at 5 GHz) than those of ICP TF (0.217 at 5 GHz) and OPGS-ICP TF (0.278 at 5 GHz) was mainly attributed to the larger resistive coupling through the silicon substrate. Moreover, OPGS-ICP TF exhibited larger k_{Re} than ICP TF because there was an additional resistive coupling through the OPGS.

Fig. 4(c) shows the measured G_{Amax} versus frequency characteristics of STD TF, ICP TF, and OPGS-ICP TF. The results show that, if the OPGS was adopted and the backside ICP etching was done, a 17.2% (from 0.662 to 0.776) and a 51.1% (from 0.55 to 0.831) increase in G_{Amax} was achieved at 5 and 8 GHz, respectively. The reason why OPGS-ICP TF exhibited higher G_{Amax} than those of STD TF was mainly attributed to the increase of Q_1 , Q_2 , and k_{Im} because of the reduction of the silicon-substrate loss and the increase of the magnetic-filed confinement. In addition, the reason why OPGS-ICP TF exhibited higher G_{Amax} than those of ICP TF was mainly attributed to the increase of k_{Im} and k_{Re} because of the increase of the magnetic-filed confinement.

Fig. 4(d) shows the measured NF_{min} versus frequency characteristics of STD TF, ICP TF, and OPGS-ICP TF. The results show that, if the OPGS was adopted and the backside ICP etching was done, a 0.682-dB (from 1.795 to 1.113 dB) and a 1.79-dB (from 2.597 to 0.807) reduction in NF_{min} were achieved at 5 and 8 GHz, respectively. The reason why OPGS-ICP TF exhibited lower NF_{min} than those of STD TF was mainly attributed to the increase of Q_1 , Q_2 , and k_{Im} because of the reduction of the silicon-substrate loss and the increase of the magnetic-filed confinement. In addition, the reason why OPGS-ICP TF exhibited lower NF_{min} than those of ICP TF was mainly attributed to the increase of k_{Im} and k_{Re} because of the increase of the magnetic-filed confinement.

V. CONCLUSION

Compared with the standard transformer, the OPGS-ICP transformer exhibits significant improvement in Q -factors (Q_1 and Q_2), magnetic-coupling factor, and $G_{A\max}$ (or $NF_{\min}$). In addition, compared with the ICP transformer, although the OPGS-ICP transformer exhibits similar Q -factor performances, significant improvement in magnetic-coupling factor and $G_{A\max}$ (or $NF_{\min}$) were achieved. These results demonstrate that the proposed combination of OPGS and backside ICP dry etching is very promising for high-performance RF-IC applications.

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Simulation Results for Nanoscale Field Effect Diode

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Abstract—Using the PISCES-IIb semiconductor drift-diffusion solver, we have simulated the current–voltage (I – V) curve of a nanoscale field-effect diode (FED) with a gate length of 75 nm and a gate oxide thickness of 2 nm. Whereas devices longer than 100 nm provide $I_{\text{ON}}/I_{\text{OFF}}$ ratios that are larger than those of comparable silicon-on-insulator MOSFETs (SOI-MOSFETs), the 75-nm device provides a very poor $I_{\text{ON}}/I_{\text{OFF}}$ ratio. A modified version of an FED is proposed, which provides an $I_{\text{ON}}/I_{\text{OFF}}$ ratio that is an order of magnitude larger than that of a comparable SOI-MOSFET for portions of its I – V curve. It appears that the FED can be considered as a viable structure for some digital circuits at these device lengths, provided that minor modifications are made to the regular CMOS process.

Index Terms—Field effect diode (FED), nanoelectronics, nanotechnology, nMOSFET.

I. INTRODUCTION

Due to problems encountered with regular MOSFETs at device lengths smaller than 80 nm [1]–[6], chief among them being the problems caused by decreasing the thickness of the gate oxide layer to obtain a large $I_{\text{ON}}/I_{\text{OFF}}$ ratio, it would be constructive to look for alternative structures that could provide larger $I_{\text{ON}}/I_{\text{OFF}}$ ratios. It has been shown that a field effect diode (FED) [7] provides a current in its ON state that is up to two orders of magnitude larger than that of a comparable silicon-on-insulator MOSFET (SOI-MOSFET) for device lengths longer than 200 nm [8]. At these device lengths, digital and analog circuits can benefit with regards to speed and power consumption if FED devices are used in their design in place of MOSFETs [8], [9].

In this brief, we present simulation results for a nanoscale SOI-FED. Interestingly, simulations show that the previously proposed FED design does not seem to provide improvements over a regular MOSFET at device lengths shorter than 100 nm. At such small lengths, injection of excess minority carriers from the source and the drain into the channel interferes with the normal operation of the device, and it does not turn off. However, a simple change in the doping profiles of the source and the drain results in a new structure that is capable of providing much improvement in the $I_{\text{ON}}/I_{\text{OFF}}$ ratio compared to an SOI-MOSFET with the same dimensions. These simulations demonstrate the advantages of an FED over a regular MOSFET at nanoscale dimensions regarding its current-handling capability and its smaller turn-off current, but, as will be shown, modifications are needed in the CMOS process to fabricate the FED.

II. FED

An FED is basically a regular SOI-MOSFET structure with two gates over its channel [7]. These gates can be biased such that either a p-n or n-p channel replaces the lightly doped or intrinsic region between the source and the drain. When a voltage is applied from the

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