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Prominent Study on Si Substrate EM Loss and Suppressing Techniques

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1. Introduction

With the emergence of RFIC SoC, the spiral inductor has been become to be a standard passive component in silicon technology. Since inductors with sufficient Q values are indispensable in many RF circuits, it is essential to develop a practical way of high Q inductors by CMOS process. The main challenge of inductors fabricated on chip arises from the lossy nature of silicon substrate [1]. The mechanisms of electromagnetic field loss in si-substrate were still ambiguous on any techniques for high Q inductor. In this paper, the substrate conduction loss (E-field loss) and the eddy current loss (B-field loss) of spiral inductors on several substrate designs have been studied.

2. Loss Mechanisms

A lossy substrate dissipates the energy of the electric field penetrating through it, and the eddy currents induced by a magnetic field also cancel part of the total inductance. The conceptual of a quasi-static state electromagnetic field in a spiral inductor on a silicon substrate show that conduction current (I_{cond}) and eddy current (I_{eddy}) are induced in the semi-conductive substrate, part of the stored electromagnetic energy is dissipated in the form of ohmic heat (Fig. 1).

The 2-port circuit model of a spiral inductor (Fig. 2) is utilized to analyze the EM loss, that the inductor body describes as the serial elements (L_s, R_s, C_p) which interacts with substrate (L_i, R_i, M) as a transformer [2], and the substrate effect describes as the shunt elements (C_{ox}, C_{sub}, R_{sub}). The dominant parameters that describe the E-field loss effect are R_{sub}. The smaller the R_{sub}, the larger the conduction current results due to electric field penetration through the silicon substrate, which in turn dissipates extra energy. The more eddy-current induced by B-field, which also in-turn energy dissipation, the smaller the R_i. The larger these two parameters, exhibits an increase on high frequency slope of frequency response of Q-factor, the higher the Q peak [3].

3. Results and Discussions

The test keys (Table I, Fig. 1) are spiral inductors on standard Si substrate (no. 1) for reference, standard substrate with grounded poly-Si shield (no. 2), the 4 nH inductor with first substrate and the second substrate implanted with high energy protons (no. 3 & 4). Test keys on standard Si substrate, their R_{sub}'s are around 1 kΩ, R_i's around 4~8 kΩ and Q around 4~5. The test keys with poly ground shield (no. 2), their R_{sub}'s are still around 1 kΩ, but R_i's increase and spread out to around 4~30 kΩ and Q around 5~9 (Fig. 3 & 4). The test keys with poly shield, bearing same order of R_{sub}'s but increased R_i's, indicate that electric field loss effects remain almost the same, while the magnetic field shielded by highly resistive grounded poly shield, which in turn increase the Q-factors. The R_{sub}'s and R_i's show that the inductance depended, while the higher the inductance, the lower the R_{sub}'s and the higher the R_i, but lower the Q_{max}. The resonant frequency shifted toward low frequency in bigger inductance's test-keys, which forced the f_{Qmax} to shift left, even though the low frequency slope higher, but the lower bandwidth of inductor does suppress the Q_{max} (Fig. 5 & 6). Inductors on different substrate designations show different degrees of effects of loss mechanisms on Q-factors. The test keys (no. 3) with proton implanted on standard Si substrate, bearing increased R_{sub}'s and R_i's, indicate that electric and magnetic field loss effects suppressed by proton implantation, which in turn increase Q-factor effectively. The test keys (no. 4) with both poly shield and proton implantation, bearing increased R_{sub}'s and further increased R_i's, indicate that proton implantation suppresses the electric field loss effect. The proton implanted poly shields provide reinforced magnetic field loss suppression, which increase Q-factor drastically to as high as 122% improvement (Fig. 7 & 8)! The resonant frequency around 13GHz doesn't move with any techniques to higher Q for a 4 nH inductor. The higher R_{sub} and R_i can raise the Q_{max} more (Fig. 9).

4. Conclusions

Substrate loss mechanisms have been studied, which give us a guideline that magnetic field loss (eddy current loss) mechanism could dominate loss of a Si-based spiral inductor on substrate with lower substrate resistance. Shielding measurements are recommended as main task for suppressing substrate loss. As spiral inductors on Si substrate with higher resistance, further increasing could be more effective to suppress substrate loss. Somehow, introducing proper shield would further help suppressing loss.

Acknowledgements

We would like to thank NDL and CIC for test-keys fabrication and INER for proton implant. This work was also supported by National Science Council under the NSC-94-2215-E-014-003.

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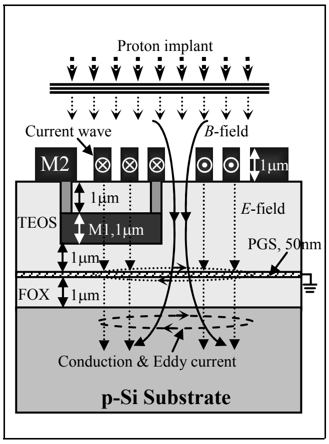

Fig. 1 Sketches of layer structures, EM-field and operations of a silicon based spiral inductor.

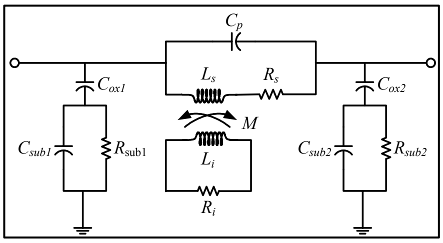

Fig. 2 2-port equivalent circuit model embedded EM-effects of a spiral inductor on a silicon substrate.

Table I Test key descriptions

Test-key	Substrate Treatment	Conditions
1	Standard Si	L: 2~5 nH,
2	Poly ground shield	L: 2~5 nH, w/ PGS (t_{poly} = 50nm, Dose: 1E12 & 5E12 cm^{-2})
3	Standard Si implanted with proton	L: 4nH, proton implant (Energy: 5MeV & 15MeV, Dose: 1E16 cm^{-2})
4	Grounded poly shield implanted with proton	L: 4nH, w/ proton (Energy & Dose same as test-key #3) + PGS (50nm, 1E12 & 5E12),

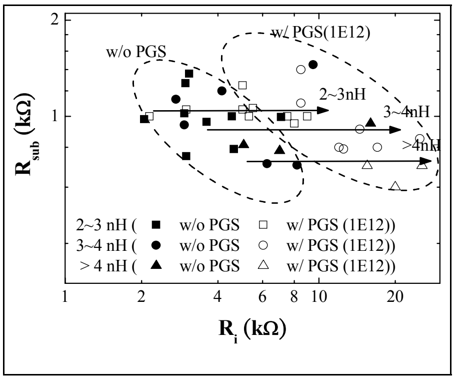

Fig. 3 The relationships on R_i and R_{sub} of all test keys in group 1 and 2.

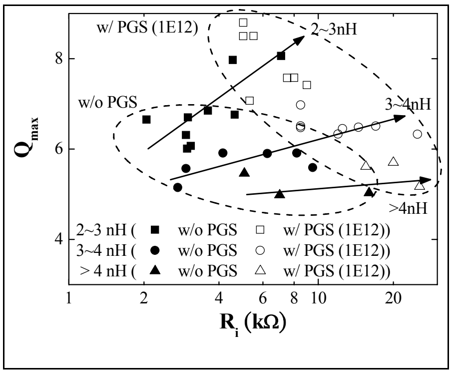

Fig. 4 The relationships on R_i and Q_{max} of all test keys in group 1 and 2.

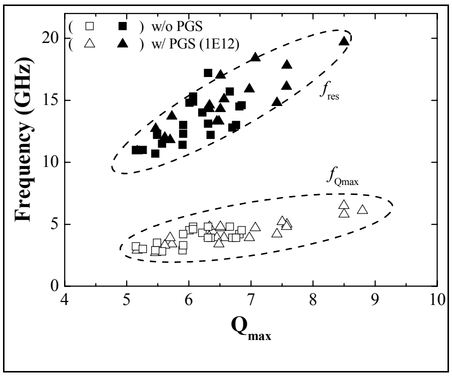

Fig. 5 The self resonant frequency and the frequency of maximum Q-value of all test keys in group 1 and 2.

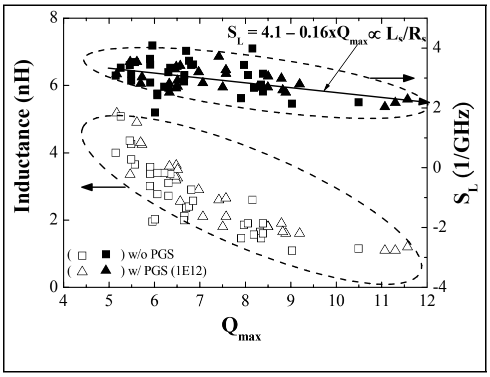

Fig. 6 The relationship on inductance or low frequency slope and Q_{max} of all test keys in group 1 and 2.

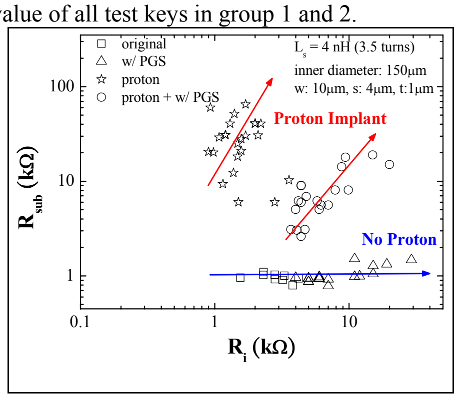

Fig. 7 The relationships on R_i and R_{sub} of all 4 test keys groups.

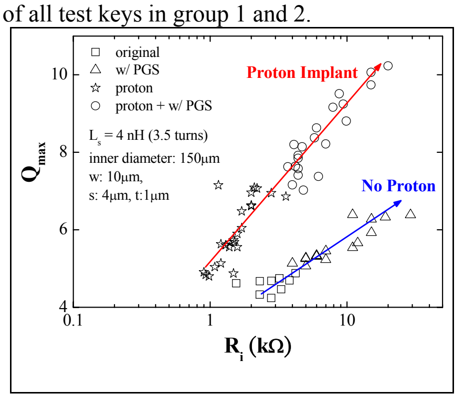

Fig. 8 The relationships between maximum Q value and R_i of inductors of all 4 test keys groups.

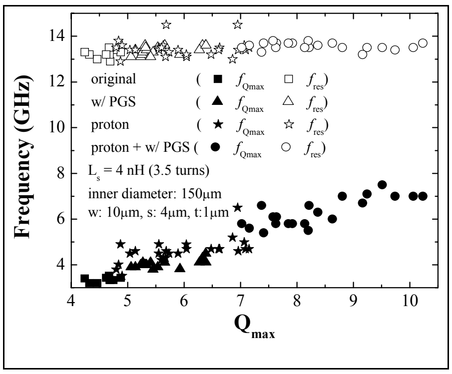

Fig. 9 The self resonant frequency and the frequency of maximum Q-value of inductors of all 4 test keys groups.