RF CMOS inductor shielded by a high-impedance surface

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Abstract: We propose a high-performance inductor based on the concept of a high-impedance surface (or artificial magnetic conductor). The inductor is shielded from the silicon substrate by a high-impedance surface consisting of a lumped capacitor and inductor. Theoretical calculations comparing the proposed inductor with a conventional inductor shielded by an ordinary metal surface show that the resonant frequency and quality factor (Q) in the millimeter-wave region are higher for the proposed inductor.

Keywords: inductor, RF CMOS, high-impedance surface, artificial magnetic conductor, quality factor

Classification: Microwave and millimeter wave devices, circuits, and systems

References

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1 Introduction

CMOS-compatible inductors with a high quality factor (Q), which should be useful in high-performance microwave and millimeter wave integrated circuits, cannot be made without reducing their parasitic resistance and substrate loss. This is usually done by using a multi-layer structure in which ground plates shield the inductor from the silicon substrate. Eddy currents on the ground plates degrade Q , however, even when patterned ground shields

are used to block them [1]. On the other hand, high-impedance surfaces [2], [3] and artificial magnetic conductors [4] have been used successfully in antenna reflectors. Arrays of patch elements (distributed circuit elements) have been used there, but the large size of distributed circuit elements makes them hard to use at frequencies below a few tens of gigahertz.

This letter therefore describes a new inductor that is shielded from the silicon substrate by a high-impedance surface consisting of a lumped capacitor and inductor. It also reports the results of theoretical calculations comparing the characteristics for this inductor and conventional inductors.

2 An inductor with high-impedance surface

Structures and equivalent circuits for the conventional and proposed inductors are shown in Fig. 1. The substrate loss described in Fig. 1 (a) by G_{sub} and C_{sub} is often eliminated by a shield metal placed on the field oxide as shown in Fig. 1 (b). The quality factor Q for the equivalent circuit shown in Fig. 1 (b) is given by

$$Q = \frac{\omega}{r_i} (L_i - r_i^2 C_i - \omega^2 L_i^2 C_i), \quad (1)$$

where ω is the angular frequency. The resonant frequency ω_0 at which $Q = 0$ is given by

$$\omega_0 = \sqrt{\frac{L_i - r_i^2 C_i}{L_i^2 C_i}}. \quad (2)$$

Q increases with increasing ω below $\omega_0/\sqrt{3}$ and then decreases because of the parasitic capacitance C_i . When the shield metal is replaced by a high-impedance surface (HIS), the equivalent circuit is the one shown in Fig. 1 (c). At $\omega_h = 1/\sqrt{L_h C_h}$, the impedance of the HIS is infinite. The parasitic capacitance C_i has no influence on the inductor Q at ω_h , where Q is given by $\omega_h L_i / r_i$, but the Q of an actual inductor is reduced by a parasitic resistance r_h in series with L_h .

Fig. 1. Structures and equivalent circuits for inductors (a) without shield metal, (b) with shield metal, and (c) with a high-impedance surface.

Figure 2 shows an implementation of the proposed inductor. The inductor L_i is formed on layer 3 ($L3$). The HIS consists of the capacitance C_h , formed between $L1$ and $L2$, and the inductor L_h . The inductor L_h may be formed on $L2$, but in ordinary CMOS LSI's the lower layers are thinner than the upper layers and therefore have sheet resistances that are larger than those of the upper layers. The parasitic resistance r_h is thus lower when L_h is placed on $L3$ as shown in Fig. 2.

Fig. 2. Implementation of proposed inductor.

3 Calculation results

The characteristics of inductors with a HIS were compared with those of conventional inductors by using the equivalent circuits shown in Figs. 1 (b) and (c) and taking into account the parasitic resistance r_h . For simplicity, both inductors (L_i and L_h in Fig. 2) were treated as straight lines and values of inductances and capacitances were obtained assuming that the metal thickness was zero. The sheet resistance of inductors was assumed to be $9 \text{ m}\Omega/\square$, which is a feasible sheet resistance for $2\text{-}\mu\text{m}$ -thick Cu [1]. The insulator between $L2$ and $L3$ was assumed to have a relative dielectric constant of 3 and to be $3.5 \mu\text{m}$ thick. The distance between the conventional inductor and shield metal was assumed to be $4.5 \mu\text{m}$. Other values used in calculations were as follows: $L_i = 0.42 \text{ nH}$, $C_i = 60 \text{ fF}$, $r_i = 2.6 \Omega$ (inductor with HIS) or 2Ω (conventional inductor), $L_h = 0.21 \text{ nH}$, $C_h = 0.16 \text{ pF}$, and $r_h = 1.3 \Omega$.

The calculated Q and effective inductances L_{eff} are shown in Fig. 3. The conventional inductor had a Q of 15.9 and an L_{eff} of 0.64 nH at 18.5 GHz . In the inductor with a HIS and no r_h , the resonance determined by $L_h(C_i + C_h)$ appeared at about 23 GHz , and the Q exceeded 20 between 23 GHz and 31 GHz . The inductor with a HIS and a r_h of 1.3Ω had a Q of 11.3 and an L_{eff} of 0.65 nH at 31 GHz . The resonance frequency determined by $L_i C_i$ was increased from 31.6 GHz for the conventional inductor to 41 GHz . The reason for this is being investigated.

Although the peak Q for the propose inductor is smaller than that for the conventional inductor, the high-impedance surface in the proposed inductor

enable the operating frequency to be increased. The performance of the proposed inductor may be improved by optimizing circuit parameters.

Fig. 3. Calculated quality factors and effective inductances.

4 Conclusion

A high-performance inductor for RF CMOS proposed here is based on the concept of a high-impedance surface. The inductor is shielded from the silicon substrate by a high-impedance surface consisting of a lumped capacitor and inductor. Theoretical calculations comparing the proposed inductor with a conventional inductor shielded by an ordinary metal surface show that the proposed inductor has a higher resonant frequency and quality factor (Q) in the millimeter-wave region. The concept of the high-impedance surface can also be applied to high-impedance transmission lines on CMOS LSI's.

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