Wireless smart sensor with small spiral antenna on Si-substrate

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Abstract

This paper presents a wireless smart sensor (WSS) with a thermoelectric sensor, a wireless transmitter and a small spiral antenna on a single package. To transmit a sensor signal, the wireless transmitter was designed to consist of an amplifier, a modulator, an oscillator, a buffer stage and an antenna. The wireless transmitter used dual pulse position modulation for low-power transmission. The fabricated transmitter has a sampling frequency of 2.6 kHz and an output carrier wave frequency of 300 MHz band due to the higher far field radiation of the transmitted signals from inside the body. The small size spiral antenna on the chip was fabricated for the transmission of carrier waves. The antenna has a bandwidth of 270–360 MHz for VSWR < 2 and a gain of ~ 40 dB. The fabricated sensor, transmitter and spiral antenna were packaged with bond-wire on a single package. The WSS consumed a power of about 16.9 mW at the supply power of 5 V. The electric field strength of the WSS was measured to be 64.6 dB μV/m at a distance of 3 m. The wireless operation of the fabricated WSS was confirmed by demonstrating that the sensor signal was modulated by the transmitter and that the modulated sensor data was transmitted through the small size spiral antenna.

1. Introduction

Sensor technology for smart sensors has advanced by the fusion of signal processing and communication technologies. Owing to advances in complementary-metal-oxide-semiconductor (CMOS) and micro-electro-mechanical system (MEMS) technologies, it is possible to fabricate such smart sensors. A smart sensor consists of transduction elements, signal conditioning circuits, a controller and a processor in a single package [1–5]. The feasibility of this concept was first demonstrated in pressure sensors in the late 1970s [2].

Low-power wireless transmitters, RF power generators and miniature antennas have been researched for smart sensors with wireless communication functions. The power supply is an important element in smart sensors. RF power generators using RF microwaves have been used for the energy source of smart sensors in our laboratory [6].

A wireless transmitter using a pulse width modulation (PWM) method to decrease power consumption has been reported [7]. It is possible to operate with a low power compared to transmitter with a conventional analog pulse modulation method, because the oscillator of the transmitter oscillates during the ON-time of the modulated pulse. However, the PWM method has a disadvantage that the power consumption varies with the operating time of the oscillator, because the duty rate of the generated PWM signal varies with the amplitude of the input signal.

Traditionally, antennas are off-chip because of their size. The size of an antenna is a key factor determining the size of Si-based wireless applications because the antenna is the largest part of a wireless transmitter [8–16]. A 300 MHz-band antenna is larger than a GHz-band antenna, because the size of the antenna is in inverse proportion to the operating frequency. Most 300 MHz-band antennas use a substrate with high relative permittivity such as a printed circuit board (PCB) to minimize the size [17,18]. In our previous work, a 315 MHz integrated antenna was reported [19], which consisted of an integrated inductor, a capacitor and bond wire type inductors had a size of 2 × 5 mm².

Silicon-based smart temperature sensors using frequency modulation [20] and RF identification (RFID) with the temperature sensor [21,22] have been reported as wireless applications. These sensors used frequency bands of 900 MHz and 2.2 GHz.

In this study, we present a wireless smart sensor (WSS) with a thermoelectric sensor and a small size spiral antenna on a Si-substrate, for which the transmission of the sensor signal by the small size antenna on the Si chips was confirmed. The WSS used a frequency of 300 MHz band, because higher far field radiation of signals transmitted from inside a body is possible.
than that when using the GHz-band [23]. Therefore, it can be applied to monitoring systems such as for animal health control and for human sensing such as future brain-machinery interfaces [24, 25]. In our previous work, a dual pulse position modulation (DPPM) method was proposed for low-power wireless transmitter [26]. This method involves two narrow pulses in a time frame. The distance ratio between the two narrow pulses describes the amplitude of data signals. The wireless transmitter consists of an amplifier, a modulator, an oscillator, a buffer stage and a spiral antenna. To minimize the size of the WSS, a small size spiral antenna was fabricated on a silicon substrate. The spiral antenna was designed as a circular spiral with 11 turns, and its resonant frequency was 300 MHz. A thermoelectric sensor device that converts a difference in temperature into electrical potential was used in the WSS. This sensor has the advantage of a small size and integration on the same chip as the signal processing circuits, because it has a high output signal and is compatible with CMOS processes. Our group has investigated the use of a thermoelectric sensor on the silicon on insulator (SOI) structure as a smart sensor chip [27]. The WSS using the thermoelectric sensor was packaged and evaluated on a PCB.

2. Design and fabrication of WSS

The WSS consists of a thermoelectric sensor, a wireless transmitter and an antenna on a Si substrate as shown in Fig. 1. The sensor signal is modulated by the DPPM method. Then, the oscillator is operated by the ON-/OFF-time of the modulated signal. Finally, the carrier wave is transmitted by the spiral antenna. In this study, the fabricated modulator, oscillator and small size spiral antenna are packaged with the sensor in a single package. The thermoelectric sensor is used for a temperature detector.

2.1. Wireless transmitter

The wireless transmitter used the DPPM method to achieve low power consumption [26]. This method involves two narrow pulses, where the data signal is described by the distance ratio (DR) between the two narrow pulses. The positions of the first and second narrow pulses are the start point of a period and the amplitude of the data signal, respectively. In Fig. 2, the modulation signal (V_{mod}) is obtained by comparing a reference signal (V_{sawtooth}) and the data signal (V_{data}). From the period \( T_{period} \) and the interval \( T_{amp} \) between the two narrow pulses, the DR is given as

\[
DR = \frac{T_{amp}}{T_{period}}
\]

The modulator consists of a sawtooth wave generator, a comparator and a narrow pulse generator as shown in Fig. 3.

The sawtooth wave was generated by the charge and discharge of capacitor (C1) and its frequency depends on the capacitance of C1 and a reference current (I_{ref}). The PWM signal was generated by an intersective method, which involves a comparison between the sawtooth wave and the data signal. The narrow pulse generator was designed to generate the two narrow pulses at the rising and falling positions of the PWM signal. To generate the narrow pulse at these positions, the narrow pulse generator used two differentiators with capacitors (C2 and C3), MOSFET loads (M4 and M5), an inverter (U3) and a NAND gate with an inversion input (U4). The rising and falling edges of the PWM signal were detected by the differentiators and inverter. Then, the signals detected by the differentiators were converted into a pulse signal, and the combined signal was outputted by U4. Two pulses with different widths were realized by adjusting the \( W/L \) ratios of M4 and M5.

Generally, ring oscillators comprise the odd number of inverters connected in a closed loop with positive feedback. The oscillation frequency is determined by the number of inverters in the ring oscillator and the sum of the high-to-low and low-to-high delays from the input and output capacitances of the inverters.

In this study, a ring oscillator was designed with a NAND gate, two inverters and a power amplifier with \( 1 \times, 3 \times \) and \( 9 \times \) buffer stages as shown in Fig. 4. When the enable signal is at a high level, the loop is enabled by the NAND gate, and the ring oscillator is operated. Otherwise, the loop of the oscillator is disabled by the NAND gate [28].

The transmitter used a temperature-independent bias generator to supply the bias voltage, and has low sensitivity with respect to temperature and the supplied power [29].

The modulator and the oscillation-controlled ring oscillator of the wireless transmitter were fabricated using 2.5 \( \mu \)m CMOS technology at Toyohashi University of Technology. This technology has been used for the fabrication of devices such as sensors and circuits. An n-type (100) silicon wafer with a resistivity of 3.38–4.65 \( \Omega \) cm was used for the fabrication of the transmitter. A p-well was formed by ion implantation with boron \((1.5 \times 10^{13} \text{ cm}^{-2}, 60 \text{ keV})\) and drive-in for 9 h. The gate oxide of the MOS (\( t_{ox} \)), which had a thickness of 56 nm, was formed by dry oxidation. Polycrystalline silicon (poly-Si) was deposited by low-pressure chemical vapor deposition (LPCVD). Then, phosphorus-doped-poly-Si gate was formed. The source and drain of the pMOS and nMOS were implanted with boron \((4 \times 10^{15} \text{ cm}^{-2}, 80 \text{ keV})\) and phosphorus \((4 \times 10^{15} \text{ cm}^{-2}, 50 \text{ keV})\), respectively. After
silicon oxide (SiO₂) was deposited using tetra-ethyl-ortho-silicate (TEOS), contact holes were defined. Then, metal was deposited in the openings to form metal lines and bond pads by aluminum sputtering to a thickness of approximately 1 μm.

2.2. Spiral antenna on silicon substrate

The operating frequency and input impedance should be considered in the design of a spiral antenna.

The characteristic of a spiral antenna depends on design parameters such as the number of turns, the outer diameter of the spiral antenna, the width of the spiral pattern and the interval between patterns. Fig. 5 shows the physical model of a spiral antenna on a silicon substrate. The inductance of the spiral antenna is represented by $L_s$ in Fig. 5(c), which can be expressed as

$$L_s = \frac{\mu n^2 d_{avg} c_1}{2} \left( \ln \left( \frac{c_2}{c_0} \right) + c_3 \sigma + c_4 \sigma^2 \right)$$

(2)

where $n$ is the number of turns, $\mu$ is the permeability, $d_{avg}$ is the average difference between the inner diameter $d_{in}$ and outer diameter $d_{out}$ and $\sigma$ is the fill ratio, defined as $\sigma = (d_{out} - d_{in}) / (d_{out} + d_{in})$. $c_i$ are coefficients in the current sheet expression: $c_1 = 1.00$, $c_2 = 2.46$, $c_3 = 0.00$ and $c_4 = 0.20$.

In the model, $R_s$ is the resistance of the aluminum layer of the spiral antenna. $C_{ox}$ is the oxide capacitance from the aluminum layer to the substrate. $R_{si}$ and $C_{si}$ are the substrate resistive loss and the substrate capacitance, respectively, which are given by the equations [31]

$$R_s = \frac{\rho l}{d_1 \delta (1 - e^{-l/\delta})}$$

(3)

$$C_{ox} = \frac{ld_1 e_{ox}}{2e_{ox}}$$

(4)

$$R_{si} = \frac{2}{ld_1 G_{sub}}$$

(5)

$$C_{si} = \frac{ld_1 C_{sub}}{2}$$

(6)

here, $\rho$ and $l$ are the resistivity and length of the spiral pattern, respectively, $d_1$ is the width of the spiral pattern, $\delta$ is the skin depth at the considered frequency, $e_{ox}$ is the oxide dielectric constant, $e_{ox}$ is the depth of the oxide, $G_{sub}$ is the substrate conductance per unit area and $C_{sub}$ is the capacitance per unit area.

As the number of turns of the spiral is increased, the operating frequency of the spiral antenna is decreased because of the increased inductance in the spiral antenna. However, in the case of the fixed $d_1$ and $d_2$ for the pattern, the operating frequency was limited even if the number of turns of the spiral is increased, because the input impedance in the spiral antenna is increased with $R_s$, $C_{ox}$ and $C_{si}$ as shown in Fig. 6(a). Here, this problem has been solved by increasing $d_{out}$. Then, impedance matching is achieved by adjusting $d_1$ and $d_2$, which can control the resistance and capacitance of the spiral antenna as shown in Fig. 6(b). When $d_1$ and $d_2$ are decreased, the reactance and capacitance of the spiral antenna increased.

For the operating frequency of 300 MHz band in this study, the spiral antenna was designed to have 11 turns and a size of 1.2 x 1.2 mm². $d_1$ and $d_2$ were set to 20 μm to optimize the impedance of the antenna.

In the following investigation we employed the commercial software package Ansoft HFSS (version 12) to characterize the performance of the antenna. In the simulation, the thickness of
the silicon beneath the spiral antenna was set to 525 μm. A SiO₂ was used as an insulator between the silicon substrate and the aluminum layer, to reduce the loss of the silicon substrate. As shown in Fig. 5(b), the thickness of SiO₂ was set to 1.5 μm. In the simulation as above, the permittivity of the silicon substrate was assumed to be 12 and that of SiO₂ was assumed to be 3.9. The simulated of the designed spiral antenna was resonated at 300 MHz, and the return loss was −17 dB as shown in Fig. 9(a).

An n-type (1 0 0) silicon wafer was used for the substrate of the small size spiral antenna. SiO₂ with a thickness of 1.5 μm was formed by wet oxidation and TEOS. For the spiral antenna pattern, a metal layer was deposited by aluminum sputtering to a thickness of approximately 1 μm. Finally, the spiral pattern was formed by RIE.

3. Experimental results and discussion

The WSS with a thermoelectric sensor, a wireless transmitter and an antenna was packaged on a PCB as shown in Fig. 7. The interconnections between the output of the sensor and the input terminal of the modulator and between the output of the transmitter and the spiral antenna were formed using bonding wire.

In order to determine the characteristics of the fabricated wireless transmitter, we used a DC power supply (ultralow noise DC source, PA15A, ShibaSoku) and a digital oscilloscope (DPO4104, Tektronix). At a supply voltage of 5 V, the generated sawtooth wave has an amplitude of 2.6 V<sub>p-p</sub> (from 0.4 to 3.0 V). Then, the output frequency was measured to be 2.6 and 2.2 kHz at 25 and 60 °C, respectively. The DR in a period of DPPM changed with the amplitude of the data signal as shown in Fig. 8(a). The change in the period of DPPM in the modulator with the change in capacitance of the sawtooth wave generator depended on the
temperature. However, as shown in Fig. 8(a), the modulator has a stable DR as a function of the input signal in each period owing to the constant amplitude of the sawtooth wave. The DPPM method has a start point of a period as the first narrow pulse. Therefore, although the period of DPPM is changed, it is possible to demodulate the received using the DPPM method.

The output frequency of the oscillation-controlled ring oscillator can be changed by varying the supply voltage. Fig. 8(b) shows the oscillator output frequency as a function of the supply voltage at 25 and 60°C. The frequency tuning range of the oscillator was found to be approximately 110–350 MHz. The output frequency was 310 MHz at a supply voltage of 5 V at 25°C, and it is linear with a correlation coefficient of approximately 0.9786. The tuning sensitivity of the oscillator was approximately 58.68 and 54.92 MHz/V at 25 and 60°C, respectively. However, the operating frequency of the oscillator varied slightly, because the WSS is applied to body sensing.

The return loss and voltage standing wave ratio (VSWR) of the fabricated small size spiral antenna were measured using a vector network analyzer (Agilent, E5062A) and a ground-signal-ground (GSG) probe (SUSS MicroTec, Z-probe, GSG-300) at the wafer level. When the fabricated spiral antenna was resonated at 300 MHz, the return loss was −28 dB at the resonant frequency as shown in Fig. 9(a). It can be concluded that the antenna obtains good quality and matching to the 50 Ω termination. The fabricated antenna has a bandwidth of 90 MHz (from 270 to 360 MHz) for VSWR < 2 as shown in Fig. 9(b). The radiation patterns of the fabricated small size spiral antenna were measured for all orientations, and the measurements were performed with a distance of 3 m between the fabricated antenna and a reference antenna (log periodic antenna, Teseq GmbH, UPA6109) in an anechoic chamber using a spectrum analyzer (Hewlett Packard, 8590D) and a signal generator (Hewlett Packard, E4432B) at the DUT level. The measured radiation patterns are shown in Fig. 10. When the antenna was horizontally oriented (x–z plane), the maximum gain was about −40 dBi because of the small size of the antenna. Whereas the gains of the antenna were −43 and −42 dBi in the x–y plane and y–z plane measurements, respectively. This performance satisfies the specifications of low-power wireless applications. The fabricated spiral antenna has the advantage of being smaller than those in previous [17–19] and is compatible with CMOS processes even though the antenna has low performance.

The electric field strength of the wireless transmitter was measured by a dipole antenna (Anritsu, MP534A) with a spectrum analyzer in an anechoic chamber. The received power of the dipole antenna was −55.5 dBm (64.6 dB μV/m) at a distance of 3 m as shown in Fig. 11. The power consumption of the wireless transmitter was measured to be about 16.9 mW at a supply voltage of 5 V. Such a WSS will be operated with lower power consumption and a smaller chip size using scaled-down CMOS technology.

The obtained temperature data from the thermoelectric sensor was modulated by the transmitter as shown in Fig. 12. The
transmission of data by the small size spiral antenna was confirmed using a receiver. Fig. 13 shows the measure setup used to the transmission of the WSS. A low-noise amplifier (LNA, 2747MB-SMAJ, cosmowave) and a dipole antenna were to confirm that the small signal was received as shown in Fig. 14. The used LNA has a gain of 25 dB at 300 MHz. The received signal using the LNA was found to have an amplitude of approximately 150 mVp–p. As a result, the fabricated WSS was able to confirm that the sensor signal was modulated by the transmitter and that the modulated sensor data was transmitted successfully by the spiral antenna. Therefore, these results indicate that the WSS chip can be used for monitoring signals from the inside of the body.

4. Conclusion

A wireless smart sensor was proposed for signal transmission from the inside of the body using a frequency of 300 MHz band due to the higher far field radiation than the GHz-band. The fabricated WSS included a thermoelectric sensor, a wireless transmitter and a small size spiral antenna in a single package. The wireless transmitter was designed and fabricated by CMOS technology. The DPPM method and an oscillation-controlled ring
transmitting 300 MHz-band carrier waves had reduced diameter of the spiral pattern. To realize a small size spiral antenna was controlled by the number of turns and the outer frequency of 310 MHz at 25°C.

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