Sensors and Materials, Vol. 8, No. 1 (1996) 001–012
MYU Tokyo

S & M 0220

An Integrated MOS Magnetic Sensor with Chopper-Stabilized Amplifier

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(Received March 15, 1995; accepted August 14, 1995)

Key words: integrated sensor, magnetic sensor, chopper stabilization, split-source-drain MAGFET

This paper describes an integrated MOS magnetic sensor with chopper-stabilized amplifier. The integrated magnetic sensor has been fabricated using the standard n-channel E/D(enhancement/depletion) MOS process technology. A sensing element with a dual-source dual-drain structure in the MOSFET suitable for the chopper driving has been developed, and is called split-source-drain MAGFET. A depletion-mode structure is used for the MAGFET to reduce the $1/f$ noise by applying a negative gate bias voltage. The integration of the chopper-stabilized amplifier with the silicon magnetic sensor leads to a reduction of the $1/f$ noise, the offset, and the offset drift of the amplifier, as well as to an enhancement of the equivalent sensitivity. The integrated magnetic sensor has a sensitivity of 5.5 V/T and the resolution of about 50 μT with 1 kHz bandwidth.

1. Introduction

In general, silicon magnetic sensors can be fabricated with standard IC processing technology. In particular, MOSFET-based magnetic sensors have been developed with relatively low-cost processing technology, and the resulting inexpensive sensor chip can be used for various applications. One of the features of silicon sensors lies in the integration of signal processing circuits on the same chip,(1) and the integration of an amplifier is a typical example. Although the sensitivity of the silicon magnetic sensors is not always high compared with those using compound semiconductors, the signal processing circuits integrated with the silicon magnetic sensor allow us to enhance its equivalent sensitivity. However, due to the relatively large $1/f$ noise, small g_m, and the large device-parameter mismatch, the MOSFET-based amplifier integrated with the silicon magnetic sensor should be carefully designed to achieve wide dynamic range and low-offset characteristics.

In this paper, we present an integrated silicon magnetic sensor with a chopper-stabilized amplifier. The chopper-stabilized amplification is useful for reducing the $1/f$ noise which is a major component of the MOSFET-based amplifier, the offset, and the offset drift of the amplifier used. Therefore, if the sensing element is designed carefully to achieve low-noise and low-offset characteristics, integrated MOSFET-based magnetic sensors with high equivalent sensitivity, low offset, wide dynamic range, high stability, and low cost can be realized. This paper describes some considerations in the design of such a high-performance integrated silicon magnetic sensor.

The amplifier has a fully differential E/D (enhancement/depletion) n-channel MOS circuit configuration.(2) Two chopping switches are realized by cross-coupled switches using the n-channel enhancement-mode MOS transistors. For the effective chopper stabilization, the polarity of the current supply to the sensing elements has to be alternated with the chopping clock. This reduces the offset due to the imbalance of the supply current to the sensing elements and the $1/f$ noise of the transistors used for current-to-voltage conversion. To do this, the sensing elements should be such that the polarity of the output signal is symmetrically changed by changing the polarity of the supply current. Conventional MOSFET-based magnetic sensors such as MOS Hall elements(3) and split-drain MAGFETs(4) are not suitable for the integrated sensor with chopper stabilization. We have developed a MOSFET-based magnetic sensor for the chopper-stabilized integrated sensor, and called it split-source-drain MAGFET because it has two drain and two source terminals. A depletion-mode structure is used for the MAGFET to reduce the $1/f$ noise by applying the negative gate bias voltage. Four sensing elements are connected to reduce the offset due to pattern misalignment.

The integrated magnetic sensor with the chopper-stabilized amplifier has the sensitivity of 5.5 V/T and the resolution of about 50 μT with 1 kHz bandwidth. The performance can be further improved by examining the optimal amplifier gain. The integrated MOS magnetic sensor with relatively high-resolution and high-equivalent sensitivity will contribute to widening the application areas of the low-cost MOS-based silicon magnetic sensors.

2. Chopper-Stabilized Amplification

Chopper stabilization has been used for many years in the design of precision d.c. amplifiers. The principle of the chopper-stabilized amplification is illustrated in Fig. 1. The input signal and the noise spectra are also shown. Two cross-coupled switches are used in the chopping operation. One is placed between the power-supply current source and the power-supply terminal of the sensor, and the other is placed at the output of the

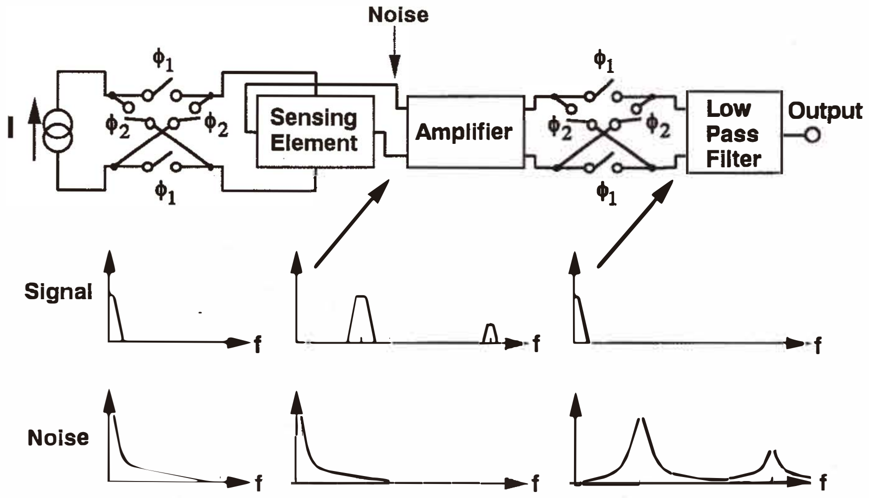

Fig. 1. Principle of the chopper-stabilized amplification.

amplifier. These switches are controlled by a chopping square wave of amplitudes +1 and −1. At the output of the sensor, the signal is modulated and translated to the odd harmonic frequencies of the chopping square waves, while the 1/*f* noise and the offset drift of the amplifier are unaffected. After passing through the second cross-coupled switch, the signal is demodulated back to the original one, and the noise has been modulated as shown in Fig. 1. This chopping operation results in the shift of the 1/*f* noise component to the odd harmonic frequencies of the chopping square wave. The 1/*f* noise density at low frequencies is now equal to the "folded-back" or aliasing noise from those harmonic 1/*f* noise components. Therefore, if the chopper frequency is much higher than the signal bandwidth, the 1/*f* noise in the signal band will be greatly reduced using this technique. The noise components shifted to high frequency can easily be removed by a low-pass filter.

For effective chopper stabilization, the first chopper should be placed just between the power-supply current source and the sensing element. This results in the reduction of the 1/*f* noise and the offset due to the imbalance of all the components other than the sensing elements. Therefore, the sensing elements should be suitable for the chopper stabilization and be designed to have low-noise and low-offset characteristics.

3. Sensing Element

For the chopper driving, the sensing element should meet two requirements: i.e., the sensing element should accept both polarities (negative and positive) of the supply current, and the polarity of the output signal should be changed symmetrically with the polarity-inverted current. Therefore, in the case of a current-output sensor, the sensing element should have the following characteristic for both polarities of the supply current, I_{supply}:

$$I_{\mathrm{out}}=S_B B I_{\mathrm{supply}},$$

where I_{out} is the output current, S_B the proportionality constant which corresponds to the sensitivity, and B the applied magnetic flux density to be measured.

Two types of MOSFET-based magnetic sensor that can be realized with standard MOS IC technology have been proposed; i.e., one is a MOS Hall element and the other is a split-drain MAGFET. However, both types are not suitable as the sensing element of the integrated sensor with chopper stabilization when we take the above-mentioned requirements into consideration. Therefore, we have developed a new MOSFET-based magnetic sensor suitable for the chopper driving, and called it split-source-drain MAGFET. Two types of devices are available as the sensing elements in standard E/D MOS IC technology; i.e., an enhancement-mode MOSFET and a depletion-mode MOSFET. The depletion-mode device is used as the sensing element to reduce the $1/f$ noise.(5) The main source of the $1/f$ noise in MOSFET is the interface state of the semiconductor surface (silicon-silicon dioxide interface) used as the channel. The contribution of the surface-channel current to the total current can be reduced using the depletion-mode device with application of a negative gate voltage.

Figure 2 shows the structure of the sensing element and its symbol. The element has two drain contacts and two source contacts in a MOSFET. The depletion-mode MAGFET is realized by phosphorus channel doping with ion implantation. The threshold voltage is set at a negative value, and the drain current at zero gate bias is denoted by I_{dss}. The gate bias condition is determined by the current supply to the MAGFET, and the device operates in the negative gate bias region under the current supply of less than I_{dss}. The operation of

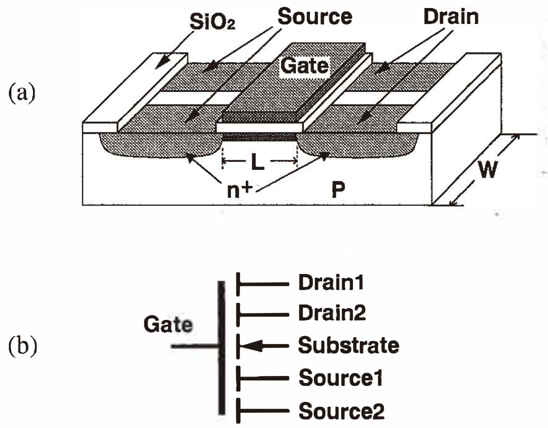

Fig. 2. Structure and symbol of the sensing element. (a) Structure. (b) Symbol.

the MAGFET is as follows. The same constant current is supplied to the source terminals. When the magnetic field is not applied, the two drains share the drain current, and the currents of the two drain terminals are balanced. A magnetic field applied perpendicular to the chip surface causes a deflection of the current lines in the channel region due to the Lorentz force. Thus the current difference between two drain terminals is a measure of the applied magnetic field. The source terminals and drain terminals can be exchanged, and the polarity of the current supply can be changed. The symmetrical structure results in a symmetrical output-current difference after exchanging the source and drain terminals.

4. Integrated Sensor Configuration

The circuit configuration of the integrated sensor fabricated using E/D n-channel MOS technology is shown in Fig. 3. The cross-coupled switches are realized by enhancement-mode n-channel MOSFETs. The gate of the MOSFETs is controlled by two nonoverlapping

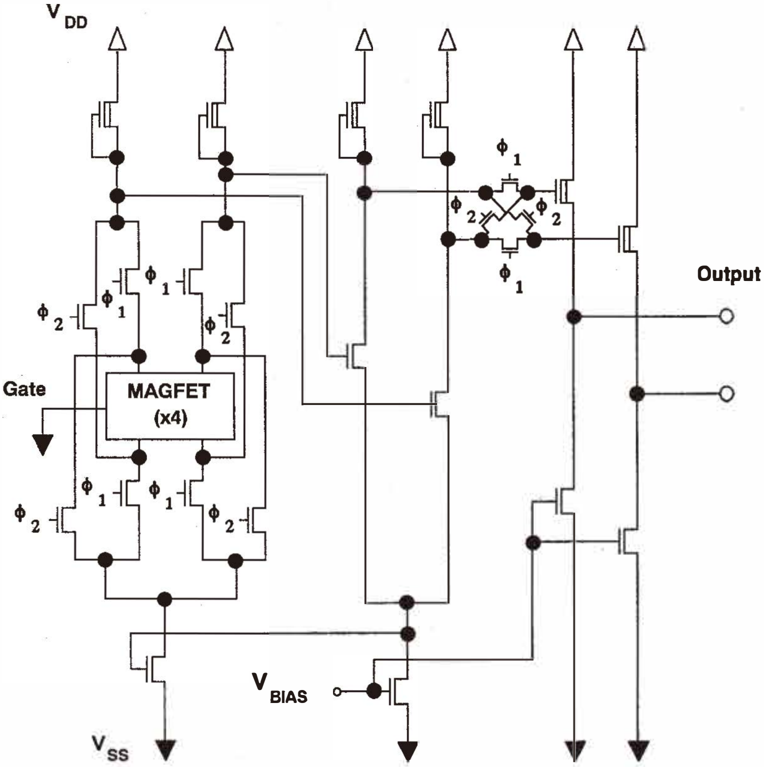

Fig. 3. Circuit configuration of the integrated magnetic sensor.

clocks. The source and drain contacts of the sensing element are connected to the current sources and the depletion-mode load transistors, respectively, through the cross-coupled switch, and thus the differential current is converted into a differential voltage. The differential voltage is further amplified by a second-stage differential amplifier. The gate of the sensing element is connected to a negative power supply; thus the element always operates under a negative gate bias condition. Two source followers are connected to the output of the second cross-coupled switch or the second chopper to observe the output.

5. Implementation and Result

The integrated magnetic sensor was designed and fabricated using the standard 8 μm E/D n-channel MOS technology. Figure 4(a) shows a micrograph of the split-source-drain MAGFET. The channel length and the channel width are both 500 μm. The split spacing is 50 μm and the gate oxide thickness is 850 Å. Channel doping for the depletion-mode operation is carried out by phosphorus ion implantation. The doping concentration is 1×10^{-12} atoms/cm^2 at 60 kV. The threshold voltage is – 4.5 V. The element is characterized by the circuit configuration shown in Fig. 4(b). The differential output current as a function of the magnetic flux density is shown in Fig. 5. A linear relationship in the measured range from –75 mT to 75 mT is obtained. The offset current is 9.4 nA for the supply current I_{ss} of

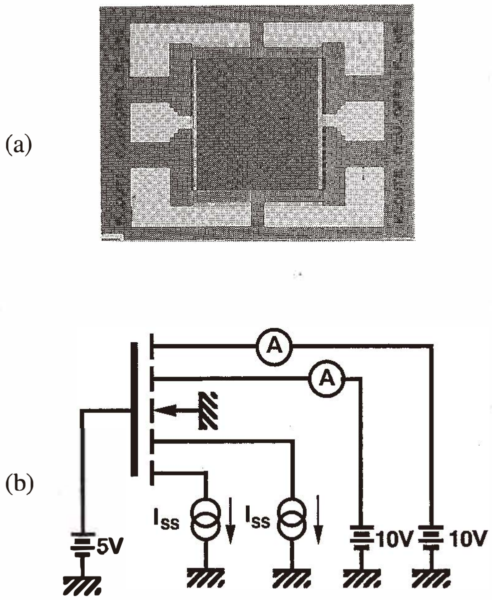

Fig. 4. Implemented split-source-drain MAGFET. (a) Split-source-drain MAGFET. (b) Measurement circuit.

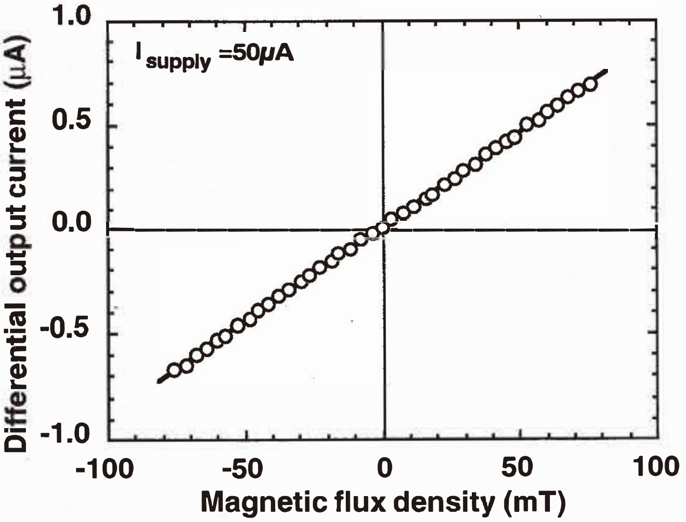

Fig. 5. Relationship between the output current and the magnetic flux density.

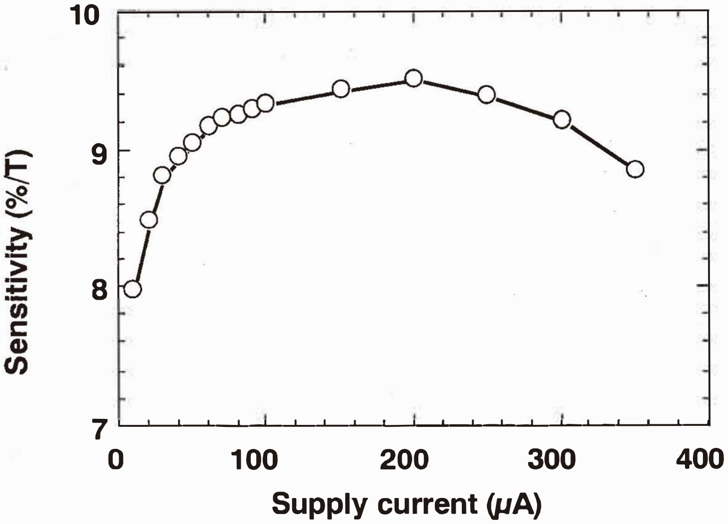

Fig. 6. Supply current dependence of the sensitivity of the MAGFET.

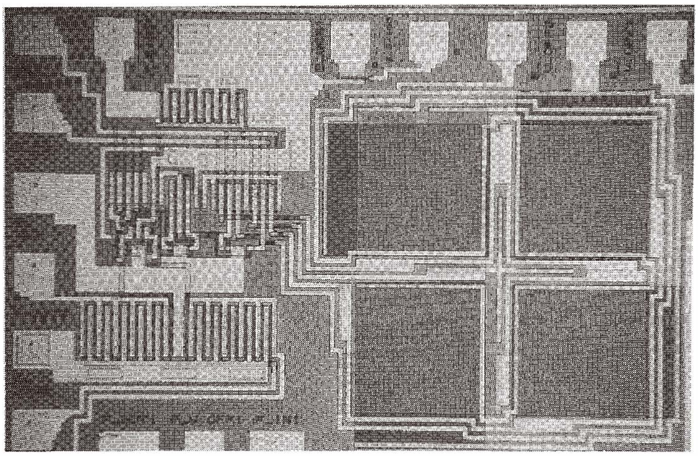

Fig. 7. Photomicrograph of the integrated sensor.

50 μA. The magnetic sensitivity is given by $S_B = \Delta I / 2 I_{ss} B \times 100\%$. The supply current dependence of the sensitivity of the MAGFET is shown in Fig. 6. The maximum sensitivity is 9.05%/T at the supply current of 200 μA.

Figure 7 shows a micrograph of the implemented integrated magnetic sensor. The integrated magnetic sensor of Fig. 3 occupies an area of about 1.8×2.5 mm^2. In order to reduce the offset current, four sensing elements are connected as shown in Fig. 8, and are used in the integrated sensor.(6) These sensing elements are arranged in different directions so that the imbalance due to the misalignment of the drain and source contacts is canceled out. The sensitivity is unchanged by the parallel connections. The output noise is reduced by the parallel connections because the 1/*f* noise is inversely proportional to the total device channel area.(7) In the measurement, a low pass filter (LPF) is connected to the output of the sensor. The cut-off frequency and the voltage gain of the LPF are 1 kHz (–24 dB/oct) and 10 (20 dB), respectively. The output voltage as a function of the magnetic flux density is shown in Fig. 9. The total magnetic sensitivity including LPF gain is 55 V/T. Therefore, the sensitivity of the integrated magnetic sensor alone is about 5.5 V/T. Good linearity is obtained in the measured range of less than 0.82 mT. Figure 10 shows the observed noise waveforms of the integrated magnetic sensor for the cases of chopping on and chopping off. It is clear that the noise is reduced by turning the chopping on. The noise and the signal responding to an applied a.c. magnetic field, the frequency and magnetic flux density of which are 100 Hz and 0.1 $\mathrm{mT_{p\text{-}p}}$ (1.0 $\mathrm{Gauss_{p\text{-}p}}$), respectively, are observed by a FFT spectrum analyzer as shown in Fig.11. The chopping frequency used is 100 kHz. The 1/*f* noise is reduced by the chopper stabilization. From Fig. 11, the r.m.s. noise in the frequency range from 0.01 Hz to 1 kHz is about 2.7 $\mathrm{mV_{rms}}$ if all the residual noise is the 1/*f* noise. Since the sensitivity including the LPF gain is 55 V/T, the resolution with the signal-to-noise ratio (SNR) of 1 in this frequency range is about 50 μT. The 1/*f* noise reduction and the sensitivity depend on the chopping frequency; thus the SNR improve-

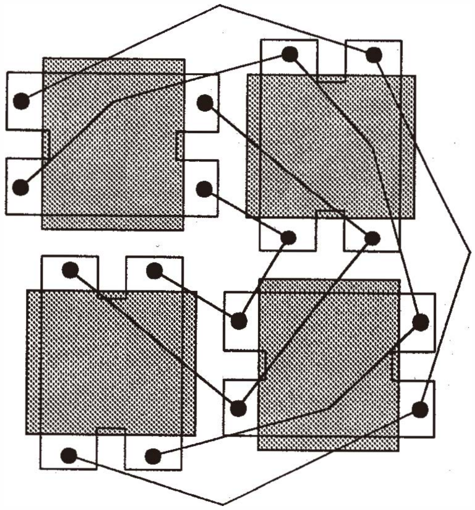

Fig. 8. Offset reduction.

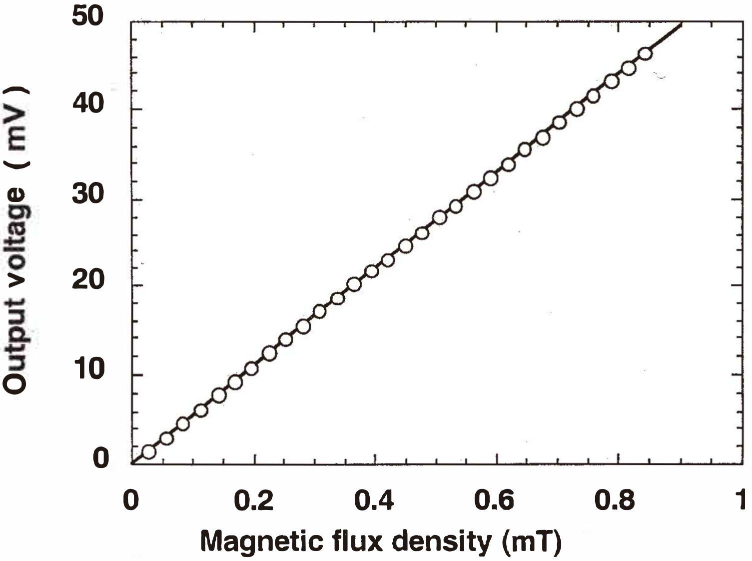

Fig. 9. Relationship between the output voltage and the magnetic flux density.

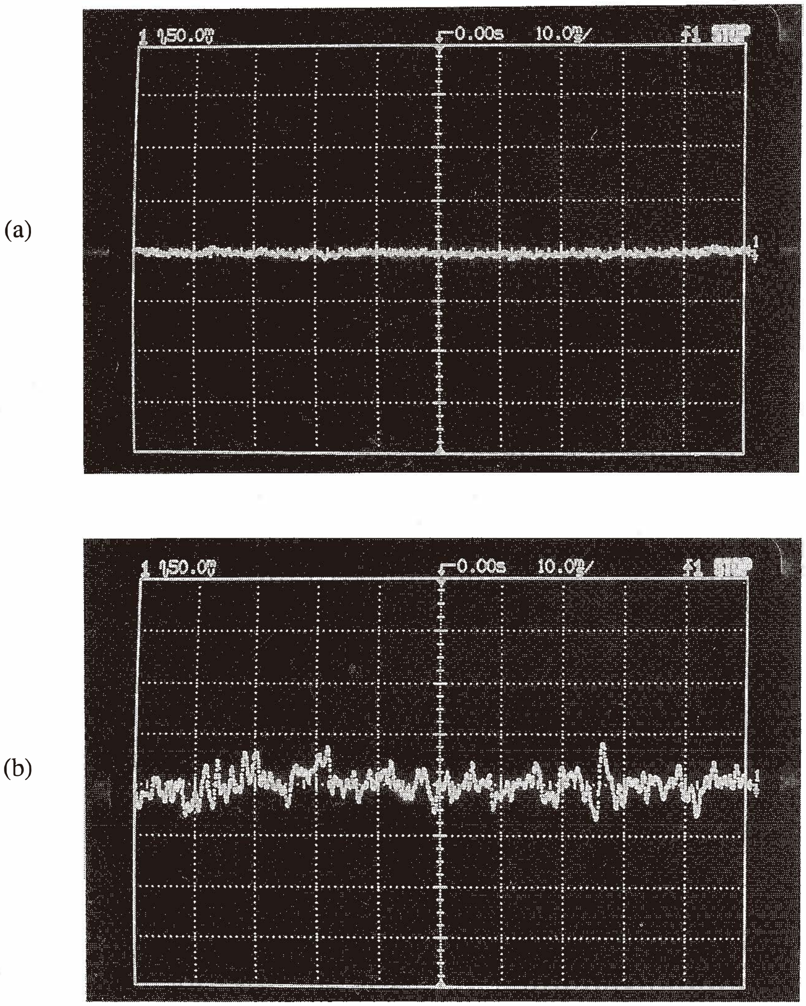

Fig. 10. Noise waveforms of the chopper-stabilized magnetic sensor. (a) Chopping on. (b) Chopping off.

ment by the chopper stabilization also depends on the chopping frequency.

Figure 12 shows the sensitivity and the improvement of the SNR as a function of the chopping frequency. The SNR is defined as a ratio of the signal responding to the 100 Hz 0.1 $mT_{p\text{-}p}$ a.c. magnetic field to the noise spectral density at 100 Hz. The sensitivity is almost constant up to the frequency of around 100 kHz, and rapidly drops with chopping

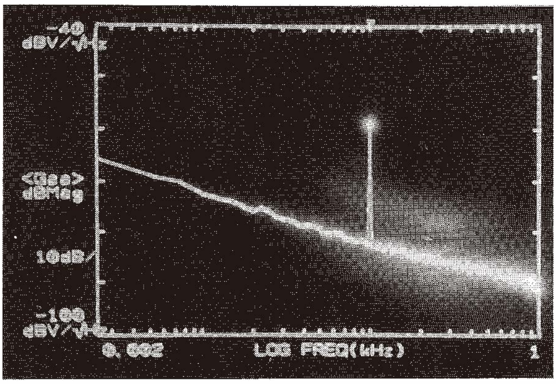

Fig. 11. Spectral density of the noise and the signal.

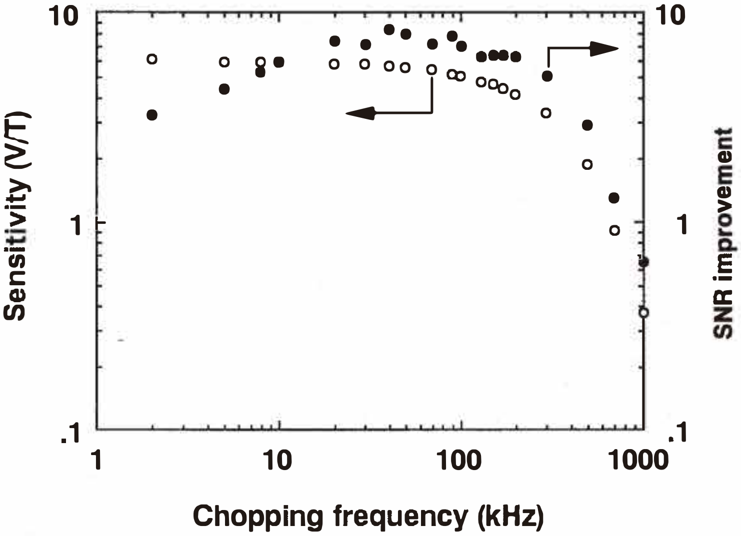

Fig. 12. Sensitivity and SNR improvement as a function of chopping frequency.

frequency exceeding 100 kHz. The noise spectral density is reduced simply by increasing chopping frequency. The optimum chopping frequency to maximize the SNR improvement is around 40 kHz. The SNR improvement of about 8 (18 dB) by the chopper-stabilized on-chip amplifier is achieved at the chopping frequency of 40 kHz.

6. Conclusions

In this paper, an n-channel integrated MOS magnetic sensor using the chopper-stabilized amplification technique is presented. A new MOSFET-based magnetic sensing element suitable for the chopper driving is developed and is used in the integrated magnetic sensor. SNR improvement using chopper-stabilized amplification has been confirmed. One of the residual noises is still the $1/f$ noise, and this may be due to the source follower used at the output of the integrated magnetic sensor. Therefore, the SNR can be further improved by using a higher-gain amplifier to convert the current output signal of the sensing element into a voltage signal. Use of CMOS technology is a candidate to achieve a higher-gain amplifier with a simple circuit configuration.

Acknowledgment

This paper is based on the research work performed in the laboratory of Professor Tetsuro Nakamura at Toyohashi University of Technology. Unfortunately, he left us midway for his heavenly abode. The authors would like to dedicate this paper to him.

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