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Review Article

Recent Advances of Amorphous Wire CMOS IC Magneto-Impedance Sensors: Innovative High-Performance Micromagnetic Sensor Chip

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We analyzed and organized the reasons why the amorphous wire CMOS IC magneto-impedance sensor (MI sensor) has rapidly been mass-produced as the electronic compass chips for the smart phones, mobile phones, and the wrist watches. Comprehensive advantageous features regarding six terms of (1) microsizing and ultralow power consumption, (2) high linearity without any hysteresis for the magnetic field detection, (3) high sensitivity for magnetic field detection with a Pico-Tesla resolution, (4) quick response for detection of magnetic field, (5) high temperature stability, and (6) high reversibility against large disturbance magnetic field shock are based on the magneto-impedance effect in the amorphous wires. We have detected the biomagnetic field using the Pico-Tesla resolution MI sensor at the room temperature such as the magneto-cardiogram (MCG), the magneto-encephalogram (MEG), and the self-oscillatory magnetic field of guinea-pig stomach smooth muscles (in vitro) that suggest the origin of the biomagnetic field is probably pulsive flow of Ca^{2+} through the muscle cell membrane.

1. Introduction

We have found a new electromagnetic phenomenon in the amorphous wire in 1993 and named it as "the magneto-impedance effect" [1], in which the impedance of the amorphous wire sensitively changed with a small external applied magnetic field when a high-frequency current was applied through the wire as a carrier. The magneto-impedance effect has basically been explained due to the skin effect in the wire using an impedance expression with Bessel's function formula [2–4]. The most important effect to utilize the skin effect is not magnetizing the inner core portion of the amorphous wire from where the magnetic noises and the demagnetizing field emanate due to the fluctuating dynamics of spike domains and the wire axial magnetization anisotropy, respectively. Thus, a new principle for sensitive micromagnetic sensors was originated. We invented a practical sensitive linear micromagnetic sensor electronic circuit in 1997 on the basis of the magneto-impedance effect using a zero-magnetostrictive amorphous wire with a pick-up coil and CMOS IC multivibrator pulse voltage generator applying the pulse current via the Schottky diode to the amorphous wire instead of the high-frequency current [5, 6]. We developed further a reliable amorphous wire CMOS IC multivibrator magneto-impedance sensor in 1999 using the analog switches instead of the Schottky diodes for realization of high temperature stability [7] and developed various stable and sensitive micromagnetic sensors [8, 9].

Electronic compasses have been developed and mass-produced by Aichi Steel Co., Japan, supported by the Japan Science and Technology Agency (JST) using the 3-axis amorphous wire MI sensor chips for the mobile phones since

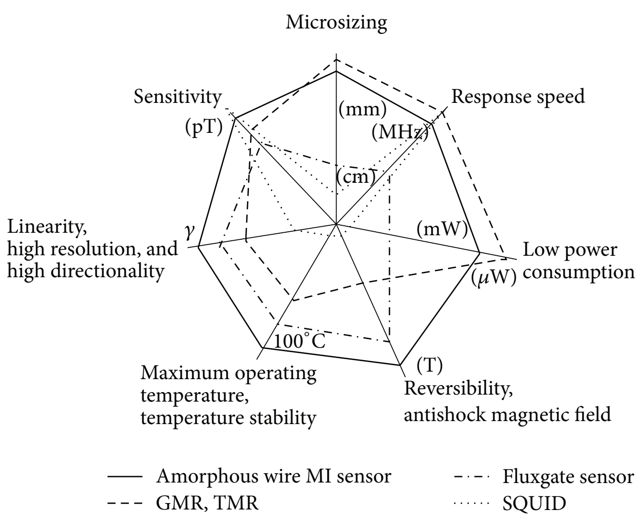


Figure 1: A comparison of seven sensor features among magnetic sensors.

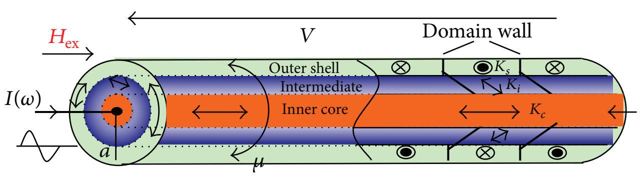


Figure 2: Domain model for amorphous wire [9].

2005, the smart phones since 2011, and the wrist watch since 2013.

We have also developed a highly sensitive magnetic sensor with 1 Pico-Tesla resolution MI sensor and applied it to detect the biomagnetic field at the room temperature such as for an in vitro biopsy fragment of guinea-pig stomach [10], the human magneto-cardiogram, the human back magneto-cardiogram, and the human magneto-encephalogram [11, 12].

2. Advantageous Features of Amorphous Wire MI Sensor

Figure 1 illustrates a comparison for the seven sensor features of linear and sensitive magnetic sensors except magnetic recordings with the GMR system [13] including the TMR [14], the Fluxgate sensors [15], the SQUID [16], and the amorphous wire MI sensor. The electronic compass installed in the smart phones and the wrist watches requires comprehensive advantageous features having a maximum area surrounded with the feature lines illustrated in the seven-radial-axis sensor comparison figure.

3. Origin of Advantageous Features of Amorphous Wire MI Sensor

3.1. Magneto-Impedance Effect in Amorphous Wires with Sinusoidal Current Application. Figure 2 represents a domain model for the nearly zero-magnetostrictive amorphous wire used for the MI sensor head [9]. The FeCoSiB ($\lambda = -10^{-7}$) amorphous wire is cold-drawn to around 15 μm diameter from the as-quenched amorphous wire of around 130 μm diameter and then tension-annealed (by UNITIKA Ltd.). The three-layer domain structure is based on the existence of the residual stresses after the in-water quenching of the amorphous wire inducing a compressive stress at the surface layer and following a tensile stress at the inner core where a strong shape anisotropy aligns the magnetization along the wire axis. A circumferential anisotropy is induced with the compressive stress and the tension anneal.

The magnetic noises are mainly due to the fluctuating magnetic domain wall displacement of the spike domains (Barkhausen noises) in the inner core. Therefore, we should avoid magnetizing the inner core region to realize the highly sensitive magnetic sensor. The demagnetizing field $\mathbf{H}_{\text{dem}} = -N_{\text{dem}}\mathbf{M}/\mu_o$ (N_{dem}: the demagnetizing coefficient, $\mathbf{M}$: the magnetization, and $\mu_o = 4\pi \times 10^{-7}$ H/m) appears mainly at both edge regions of the inner core, which strongly decreases the magnetic sensor sensitivity for downsizing the sensor head length. Thus the most important feature of the magneto-impedance effect is to avoid the inner core magnetization of the amorphous wire utilizing the skin effect for realization of the sensitive and microsize head magnetic sensors.

Figure 3 illustrates one of the most original experimental results of the frequency characteristics of the impedance Z of an amorphous wire with 5 mm length and 30 μm diameter magnetized with an ac current $I(\omega)$ for application of an external static magnetic field $H_{\text{ex}} = 0$ and 10 Oe [1].

The impedance Z of a magnetic wire is expressed as follows [3]:

$$Z = \frac{R_{\text{dc}} ka J_0(ka)}{2J_1(ka)},$$
$$R_{\text{dc}} = \frac{\rho \ell}{\pi a^2}, \quad k = (1 - j)\,\delta, \quad \delta = \left(\frac{2\rho}{\omega\mu(H_{\text{ex}})}\right)^{1/2}, \tag{1}$$

where R_{dc} is DC resistance, ρ the resistivity of the amorphous wire (130 $\mu\Omega$-cm), ℓ the wire length, a radius of the wire, δ the skin depth, ω the angular frequency of an applied current, and μ the transverse (circumferential) maximum differential permeability.

When $\delta \gg a$ (no skin effect; $\omega \ll 2\rho/\mu a^2$),

$$Z \fallingdotseq R_{\text{dc}} + j\omega L, \qquad L = \frac{\mu\ell}{8\pi}. \tag{2}$$

When $\delta \ll a$ (strong skin effect; $\omega \gg 2\rho/\mu a^2$),

$$Z \fallingdotseq \frac{(1 + j)\, aR_{\text{dc}} (\omega\mu(H_{\text{ex}}))^{1/2}}{2(2\rho)^{1/2}} \quad (\text{Magneto-Impedance effect}). \tag{3}$$

The sensitivity of the magneto-impedance effect is

$$\frac{\partial |Z|}{\partial H_{\text{ex}}} = \frac{A\mu^{-1/2}\partial\mu}{\partial H_{\text{ex}}}, \qquad A = \frac{\rho^{1/2}\omega^{1/2}\ell}{4\pi a}. \tag{4}$$

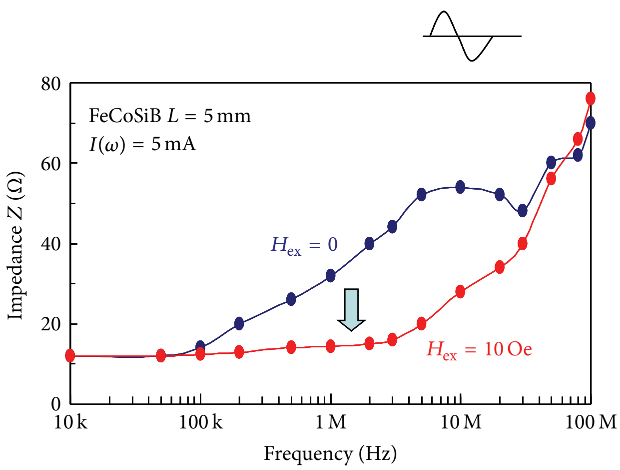


Figure 3: Frequency characteristics of the impedance of an amorphous wire with a sinusoidal current for external static magnetic field $H_{ex} = 0$ and 10 Oe, respectively [1].

It is suggested that a sensitive micromagnetic sensor would be realized to use a thinner amorphous wire maintaining a high value of ℓ/a as shown in (4). Increasing the value of ω should be considered with influence to $\mu^{-1/2}\partial\mu/\partial H_{ex}$ in which μ becomes a complex form $\mu = \mu' + j\mu''$ including the spin rotation resonance at high-frequency magnetization.

A theoretical analysis of a minimum magnetic noise spectral density β for single domain magnetization rotation model in the amorphous wire magneto-impedance effect has been presented as follows [17]:

$$\beta = \left(\frac{2\alpha k_B T}{\gamma M_s \pi D \ell}\right)^{1/2}, \tag{5}$$

where T is the absolute temperature, α the magnetic damping constant, k_B the Boltzmann constant, γ the gyromagnetic ratio, and M_s the saturation magnetization; D and ℓ are the diameter and the length of the amorphous wire, respectively.

Considering the typical parameters of the Co-rich amorphous wire, we could estimate the value of β. When a magnetic noise is measured over a bandwidth of 1 Hz, a 1 cm long wire yields β of around 10 fT at the room temperature. Thus, we could realize ultrahigh sensitive micromagnetic sensor with a magnetic noise of around fT order except the electronic circuit noises using the magneto-impedance effect [11, 12].

Although a high sensitive micromagnetic sensor would be possible using the magneto-impedance effect expressed in (3) and (4), we should newly develop a method to realize a highly linear detection characteristic instead of the method to apply a bias magnetic field adopted for the GMR type sensors, because the bias magnetic field is easily and irreversibly changed with a large disturbance magnetic field of the strong magnets such as NdFeB.

3.2. Amorphous Wire CMOS IC MI Sensor Circuit with Pulse Train Current Magnetization, Pick-Up Coil, and Analog Switches. We developed an amorphous wire CMOS IC multivibrator type microlinear magnetic field sensor for industrial usage MI sensor chip as illustrated in Figure 4 [7].

3.2.1. Amorphous Wire Magnetization Current Generated by CMOS Inverter Multivibrator. We adopted the CMOS IC inverter multivibrator generally used as the timing pulse circuit in the personal computer as a pulse train generator for amorphous wire magnetization via a differentiation circuitry and two time delay inverters. A pulse current train is illustrated in a photograph in Figure 5(a) and corresponds to a sinusoidal current with a dc bias current as illustrated in (b). Thus a pulse current with the rising time of 10 ns corresponds to a sinusoidal current with around 50 MHz, which induces a strong skin effect in the amorphous wire. A dc component of the pulse train current acts to make a single domain in the surface layer of the amorphous wire so that the magnetization in the surface layer is only due to the magnetization rotation with the smallest magnetic noises as illustrated in Figure 6.

In Figure 6, the total energy E of the magnetization rotation system is

$$E = -K_u \cos^2\theta - M_s H_p \cos\theta - M_s H_{ex} \sin\theta, \tag{6}$$

where K_u is the uniaxial anisotropy energy for the circumferential direction of the amorphous wire surface layer.

Then θ is decided by $\partial E/\partial\theta = 0$:

$$2K_u \cos\theta \sin\theta + M_s H_p \sin\theta - M_s H_{ex} \cos\theta = 0. \tag{7}$$

Measured results of the magneto-impedance characteristics in the amorphous wire magnetized with the pulse current have been represented in Figure 7 [5].

A highly sensitive magneto-impedance effect showing an impedance change rate $(Z(H_{ex}) - Z(0))/(Z(0)\Delta H_{ex})$ of more than 100%/Oe has been obtained almost independently the pulse intervals. However, a dc bias magnetic field is necessary to construct a linear magnetic sensor. In addition, a negative feedback circuitry is necessary for construction of a highly linear and nonhysteresis magnetic sensor.

3.3. High Linearity without Hysteresis Using Pick-Up Coil and High Directionality. We have set a pick-up coil around the amorphous wire to constitute a highly linear magnetic field sensor.

When a sufficient large pulse magnetic field H_p (= $I_p/2\pi a$) is applied with the rising time t_r to the amorphous wire as shown in Figure 6, a magnetization change rate ΔM along the wire axis is

$$\Delta M = M_s \sin\theta \left(H_p = 0\right) = \left(\frac{M_s^2}{2K_u}\right) H_{ex}. \tag{8}$$

The pick-up coil pulse voltage e_p (= $N\Delta\phi/t_r$; N: number of coil turns, $\Delta\phi = S\Delta M$: magnetic flux change in the surface layer cross section area S of $\pi\delta(2a - \delta^2)$) is

$$e_p = GH_{ex}, \tag{9}$$

$$G = \frac{\pi\delta\left(2a - \delta^2\right) N M_s^2}{2K_u t_r}, \quad \delta \risingdotseq \left(\frac{2t_r\rho}{\mu}\right)^{1/2}. \tag{10}$$

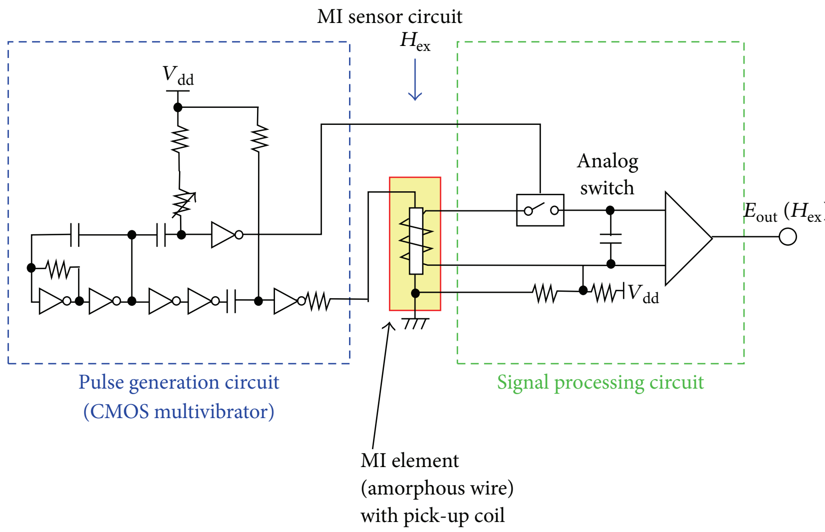


Figure 4: Amorphous wire CMOS IC multivibrator type MI sensor for industrial usage.

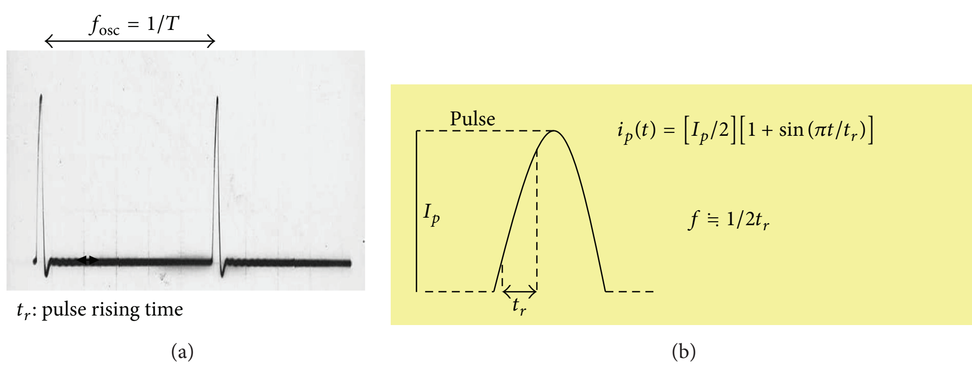


Figure 5: Pulse train current for amorphous magnetization in (a) and explanatory illustration for a correspondence between a pulse current and a sinusoidal current biased with a dc current in (b).

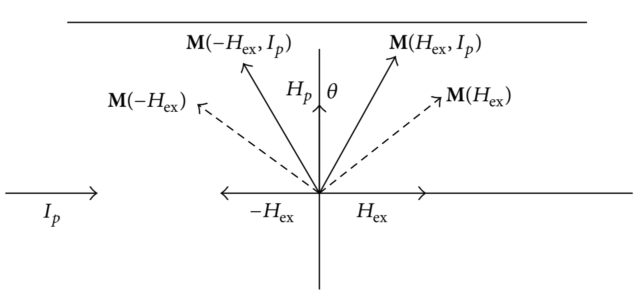


Figure 6: Magnetization rotation model in the surface layer of an amorphous wire at strong skin effect; I_p and H_p: wire magnetization pulse current and pulse magnetic field, respectively, $\mathbf{M}$: magnetization vector, H_{ex}: external axial magnetic field, and θ: angle of $\mathbf{M}$ against the circumferential direction.

The pulse magnetization magneto-impedance gain G in (10) is adjustable with the parameter adjustment of the differentiating circuitry as illustrated in Figure 4. The time duration of the analog switch in Figure 6 is adjusted to pick up only the pulse voltage as represented in (9) and cut the following oscillatory ringing noise voltage.

Thus we have created a highly linear without any hysteresis micromagnetic field sensor using a simple digital type circuitry without any negative feedback circuit as illustrated in Figure 4.

Figure 8 illustrates measured results of dc magnetic field detection characteristics of an amorphous wire CMOS IC magneto-impedance sensor (MI sensor) [18, 19] as illustrated in Figure 4 developed by Aichi Steel Co., supported by the Japan Science and Technology Agency (JST) during 1999–2002.

A high resolution micromagnetic sensor with a noise level (nonlinearity) of around 0.0125% of the dynamic range full scale was first developed, which is available for industrial mass production with a high temperature stability for −40~85-degree C operating temperature range.

The industrial mass production type magneto-impedance element (MI element) is fabricated by Aichi Steel Co., as illustrated in Figure 9 [19].

An amorphous wire is set by a microrobot on a patterned coil under part and after that an upper part patterned coil is plated followed by forming the coil. Two electrodes of the amorphous wire ends are formed with plating. A coil pitch of the plated patterned coil is possible to be up to 2 μm.

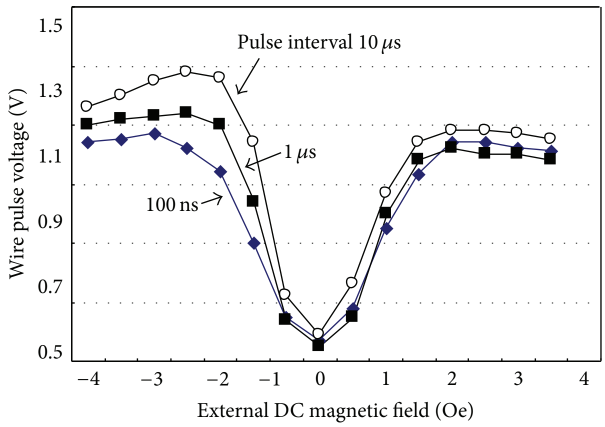


FIGURE 7: Measured results of the magneto-impedance characteristics in a 30 μm diameter, 5 mm length amorphous wire magnetized with a pulse train current 30 mA pulse height, 5 ns pulse half width with various pulse interval [5].

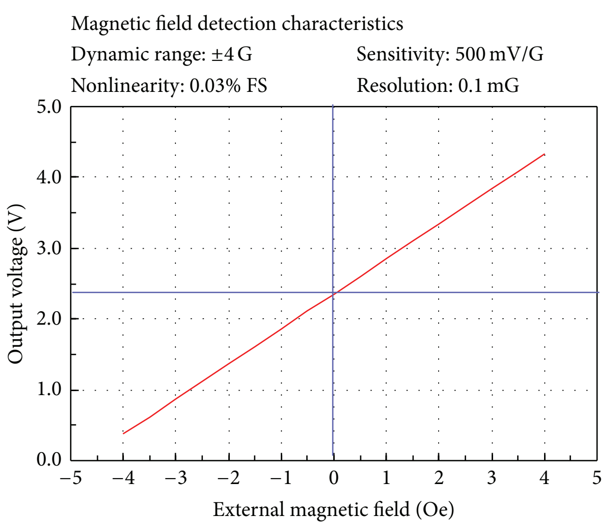


FIGURE 8: E_{out} versus H_{ex} characteristics of the amorphous wire CMOS IC MI sensor developed by Aichi Steel Co.

The amorphous wire CMOS IC MI sensor shows almost 100% directionality as represented in Figure 10 due to the high aspect ratio of the amorphous wire such as the ratio $\ell/D = 45$ for ℓ and D of 520 μm and 11.5 μm, respectively, and the high resolution linear characteristics as shown in Figure 8.

4. Electronic Compass for Smart Phones and Wrist Watches

Figure 11 illustrates photographs of the amorphous wire CMOS IC electronic compasses chips for the smart phones [19]. Three orthogonal axis amorphous wires of 10 μm diameter and 0.4 mm length each constitute a geomagnetic field vector MI sensor head. The resolution of the horizontal plane direction detection is 0.1 degrees. The pedestrian navigation system in the smart phones is composed of the electronic compass for holder's horizontal plane direction sensing and

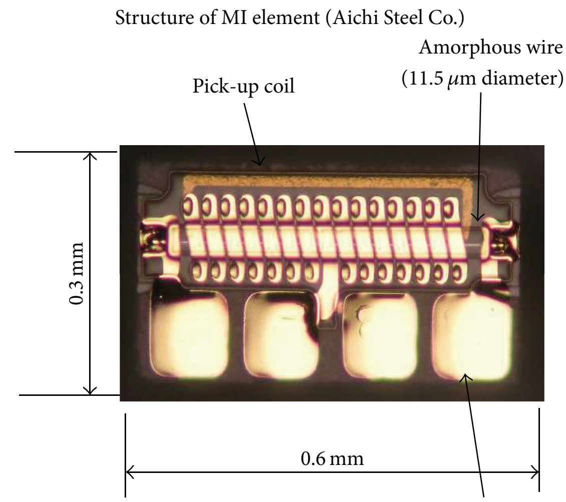


FIGURE 9: Mass production type amorphous wire MI element fabricated by Aichi Steel Co.

the GPS for holder's position sensing with the fact that the holder finds the aimed direction for walking in a headed city map in the display.

The electronic compass chips using the amorphous wire CMOS IC MI sensor have also been installed in the wrist watch since 2013, in which the performance of the MI sensor chip (AMI 306) is the geomagnetic field detection of 160 nT resolution for a dynamic range of ±1.2 mT (12 Oe) and a low current consumption of 150 μA. The ultralow power consumption is due to the pulse interval independency for the pulse magneto-impedance effect as shown in Figure 7. A true circle shape at the cross section of the amorphous wire minimizes the circumferential magnetization losses with the wire current.

Highly sensitive sensor chips have also been developed as the motion sensor chips with the gyro (rotation angle velocity) sensing performance of the amorphous wire CMOS MI sensor.

5. Pico-Tesla Resolution MI Sensors and Biomagnetic Field Sensing

A handy ultrahigh sensitive magnetic sensor with a resolution of around 1 Pico-Tesla (10^{-8} Gauss) using the amorphous wire CMOS MI sensor has been developed [10–12], in which a differential type sensor head using an amorphous wire of 8 mm length with two short pick-up coils at both ends connected antiserially for cancelling any uniform background magnetic noises. Electronic circuit noises are suppressed adding the notch filters.

Figure 12 represents some examples of detection of the biomagnetic signals: (a) oscillatory periodical magnetic field generated from a guinea-pig smooth muscle preparation of 4 mm width, 8 mm length, and 0.3 mm thickness set in a phosphate buffered saline solution (Knobs) (in vitro) [10], a human magneto-cardiogram at the chest in (b) [11], and

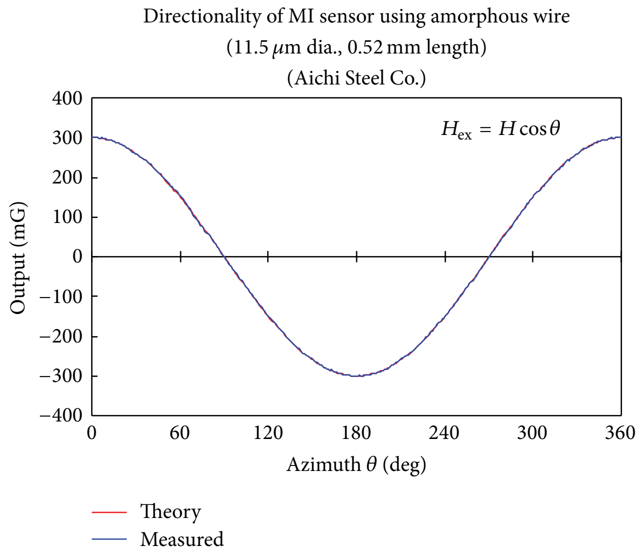


FIGURE 10: Directionality of an amorphous wire CMOS IC MI sensor.

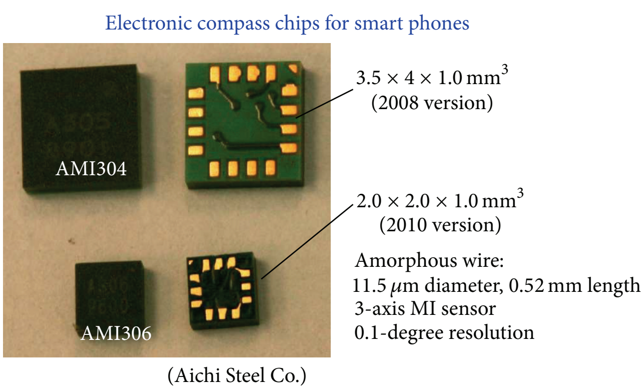


FIGURE 11: Electronic compass chips using 3-axis amorphous wire CMOS IC MI sensor.

a human back-side (left shoulder blade bottom position) magneto-cardiogram in (c) [20].

In (a), an amorphous wire sensor head of 30 μm diameter and 8 mm length in an 800-turn wound coil is set outside the surface of the plastic physiological solution (Knobs) case in parallel with the biopsy fragment width direction. A distance between the sensor head and the biopsy fragment is around 2 mm. The biopsy fragment lives through around 3 hours in the solution and actively generates the self-oscillatory bioelectromagnetic signal itself at the solution temperature at 30–38 degrees C.

In the physiology, sequential electromagnetic activities in the smooth muscle organs such as the heart and other viscera have been observed as follows: (1) origin of the action potential pulse triggered with a pacemaker cell nervous electric pulse signal, (2) the Ca^{2+} flows into the muscle cell with a delay time of around 100 ms through the cell ion channels open by the action potential pulse, and (3) the muscle tension occurred after combination of the Ca^{2+} with the cell protein Troponin C [21].

We consider a possibility to detect physiological information differs from the electrocardiogram (ECG) in the magneto-cardiogram (MCG) on the basis of these measured results. We may assume that the back MCG reflects the Ca^{2+} flow (electric current) into the muscle cells membrane showing a pulse time lag against the pulse action potential as observed in Figures 12(a), 12(b), and 12(c). A magnetic stimulation in Figure 12(c) is application of an extremely low frequency (ELF) small magnetic field used in the Magneto-Protonics principle [22–24], in which the small ELF magnetic field is predicted to elevate a production rate of the adenosine-triphosphate (ATP) in smooth muscle cells and promote the blood flow.

6. Future Applications

We may clearly estimate the progress processes of the amorphous wire CMOS IC sensitive micromagnetic sensors for the industrial and personal usages on the basis of the abovementioned comprehensive advantageous features as follows:

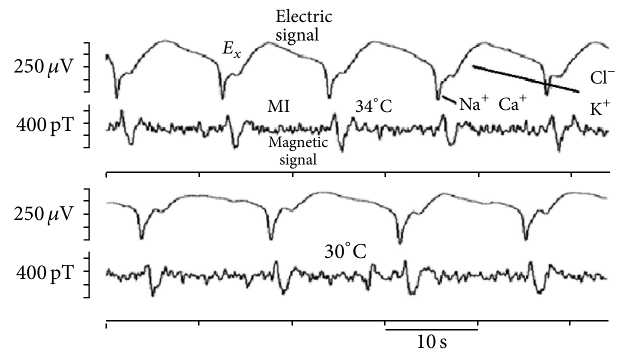
(1) Sensitive micromagnetic sensor chips in the electronic compasses for the smart phones and mobile phones, the wrist watches, the tablets, and various personal information terminals connected to the Internet. Various applications for social security systems such as the car parking controls and the personal daily behavior monitoring are widely under development.

(2) Ultrahigh sensitive magnetic sensors for the biomagnetic sensing for estimation and prediction of the ELF physiological magnetic stimulation (PMS) effects for the arousal preventing drowsy driving without “the rebound sleep” and the blood flow activation for health [25, 26]. Brain activity improvement for elderly persons is also hopeful.

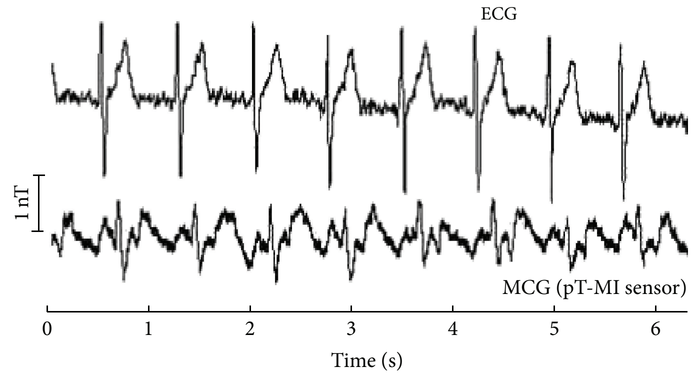
(3) GHz high-frequency magneto-impedance effects [27–31] which could be hopeful for applications such as the personal magnetic telecommunications in the vehicles.

7. Conclusions

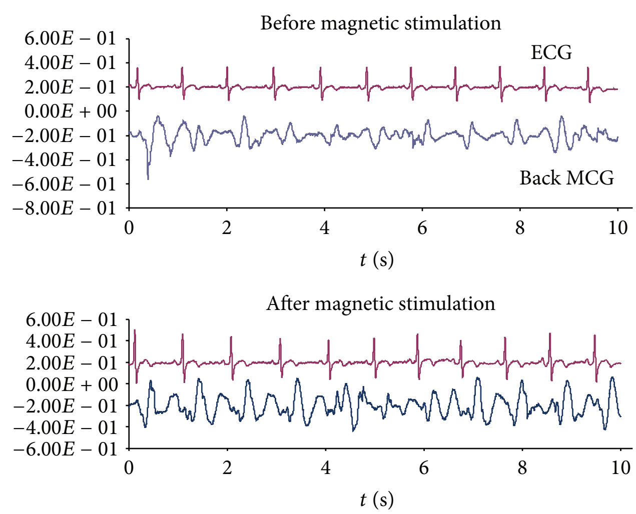
We have analytically reviewed recent advances of the sensitive linear micromagnetic sensors adopted in the mobile phones, smart phones, and the wrist watches as the electronic compass chips. We evaluated a comprehensive feature of magnetic sensors suitable to be adopted in the electronic compass chip considering seven features of the microsizing, the small power consumption, the sensitivity, the linearity and directionality, the maximum operating temperature, the reliability and reversibility of antishock magnetic field, and the response speed, in which a quick response magnetic sensor is under development. The amorphous wire CMOS IC magneto-impedance sensor has a maximum area surrounded



(a) Guinea-pig stomach biopsy fragment (in vitro)



(b) Human chest magneto-cardiogram



(c) Human back magneto-cardiogram before and after a magnetic stimulation

Figure 12: Biomagnetic field sensing using a Pico-Tesla resolution amorphous wire CMOS IC MI sensor.

with feature lines on a seven-radial-axis sensor evaluation figure (Figure 1). Theoretical explanation for mechanisms generating these features was summarized on the basis of the magneto-impedance effect. An exciting application field of the sensitive microsensor operating at the room temperature was introduced in the biomagnetic sensing using a Pico-Tesla resolution magnetic sensor.

We have not yet established a construction method of a quick response magnetic sensor such as a GHz response sensor although electronic compass chips have been mass-produced. The high-frequency operation sensor electronic circuitry needs the distributed parameter circuit technology with the impedance matching suppressing distributed power losses. The surface magnetic smoothness of amorphous wires sensitively affects the sensitivity and the power losses in high-frequency magneto-impedance sensors with very strong skin effect.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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