Observation of Water Level and Temperature Properties by using a Giant Magnetoresistance-Spin Valve Film

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The water level and temperature properties for the cooling system of potassium titanyl phosphate laser systems were observed. The middle point of the GMR-SV magnetoresistance curve is set in the neighborhood of high magnetic sensitivity (2.8 %/Oe). The experimental results for resistance dependence on water height and temperature showed linear regions with rates of 0.4 Ω/mm and 0.1 Ω/°C, respectively. The proposed results were found to be for adjusting the water level and temperature in the laser cooling system.

Keywords : GMR-SV (giant magnetoresistance-spin valve) film, water level and temperature, cooling system, sensor unit, MR (magnetoresistance) curve

1. Introduction

Currently, there is a trend in societies towards rapid increases in aging-related diseases caused by increase in elderly populations. Benign prostatic hyperplasia (BPH) is a typical aging disease, occurring in up to 50% of males in their 50 s, 60% of males in their 60 s, and 70% of males in their 70 s [1]. It has especially increased in males over 80 and is increasing rapidly compared with other chronic aging diseases [2]. Although a subcapsular prostatectomy is the best operative treatment for BPH, patients tend to avoid this operation because of its various demerits, including the possibility of serious complications such as bleeding, stricture of the urethra, incontinence, dysuresia, or electrolyte metabolism; the implantation of an indwelling catheter; and a long hospitalization period, averaging about 5-6 days [3].

On the other hand, the development of medical laser treatment devices has led to the use of lasers to treat BPH as a minimally invasive therapy technique [4]. In particular, subcapsular prostatectomy using a KTP (potassium titanyl phosphate) laser is in active application [5]. As in the case of medicinal therapy and transurethral prostatectomy surgical methods, BPH treatment has seen the development of minimally invasive treatments, such as exeresis and freeze therapy, using the expanding skills of urethral prostate, prostate urethra stand and laser [6].

A KTP laser has a wavelength of 532 nm, which lies in the green portion of the visible spectrum. This wavelength is heavily absorbed by oxy-hemoglobin, rather than water, and hence is efficient for treating organs that have abundant blood vessels, such as the prostate [7]. Additionally, the penetration depth of a KTP laser is on average about 0.8 mm, which is outstanding from the view of surgery because the heat does not spread out to immediate hemostasis and neighbor texture by permeating the heat into surface layer of the tissue [8]. Medical KTP laser technologies require stable and high-capacity power supply units, resonators to generate and emit the laser beam, a cooling system, an MPU controller, a display, and many types of sensors [9].

Several research groups have reported on the interdisciplinary and experimental results for biosensor and medical device development by using giant magnetoresistance-spin valve (GMR-SV) [10]. Especially, for the detection of biomolecular biosignals, the typical biosensor is composed of a kernel device which selectively reacts on a unique species by mixing a biological recognition system and a physicalchemical transducer [11]. A suitable biosensor will support research into the magneto property measurement of Fe inside hemoglobin and the micro-trap of the magnetic phenomena caused by the biochemical property of biomolecules [12]. However, there is not reported as the paper for one macroscopic point that a water level and temperature sensor unit based on a GMR -SV film for application as medical device. In this research,

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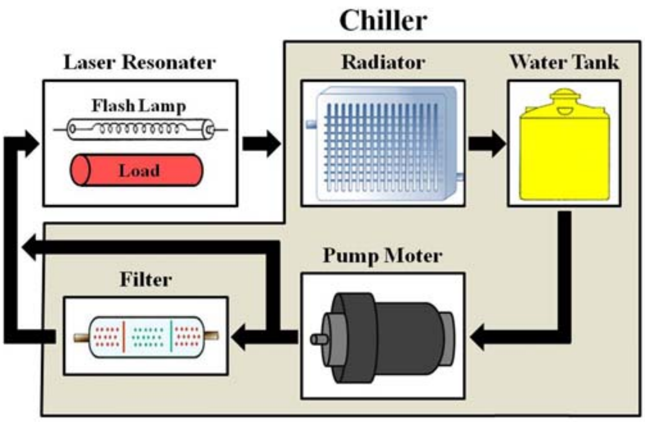

Fig. 1. (Color online) A schematic of a conventional cooling system and resonator used for a KTP laser system. The a water level and temperature sensor unit with a highly sensitive GMR-SV film as is set inside the water tank.

a multi-layer, thin-film spin valve device or sensor, with highly sensitive magnetic properties that are applicable to medical system without photolithograph process, was produced and its magnetoresistance investigated. To detect the temperature and level of water inside medical cooling system, a patterned device by using a shadow mask was prepared.

A schematic of a conventional cooling system and resonator used for a KTP laser system is shown in Fig. 1. As shown in the diagram, the cooling system for maintaining a stable resonator temperature is composed of a radiator, a water tank, and a pump motor and filter. The inside of the water tank is equipped with various sensors. To maintain the temperature of the inner water tank at below 28 °C, research and development of water level and water temperature sensors as well as velocity control techniques are required. Water level and temperature sensors based on GMR-SV films that can detect changes in the magnetic field strength have been fabricated [13-15]. We researched the sensitivity characteristics of these water level and temperature sensors for application in a KTP laser system used for treating BPH.

2. Experimental Method

The cooling system device for water level and temperature sensor was manufactured to have a multilayer structure of corning glass/Ta(5 nm)/NiFe(8 nm)/Cu(2.5 nm)/NiFe(4 nm)/IrMn(8 nm)/Ta(5 nm). The layers were deposited using a dc magnetron sputtering super-vacuum chamber system with four mounted targets. First, corning glass was cut into 1.4 × 1.4 cm^2 pieces and cleansed by dipping in acetone and alcohol after immersion in $CHClCCl_2$ with ultrasonication for 30 min to remove surface organic or foreign material. Finally, the substrates were rinsed with distilled water and left to dry. The resulting thin film was metalized at room temperature under the following fabrication conditions: primary degree of vacuum of less than 2.0×10^{-6} Torr and an Ar partial pressure of 2×10^{-3} Torr. The distance between the 3" target and the sample was about 80 mm. To ensure that the thin-film formation remains independent of the deposition layer formation, the mixing of target plasmas had to be prevented; this was achieved by installing a crossover shaped shutter comprising a stainless steel plate. The deposition rates of the four targets used, Ta, Cu, $Ni_{80}Fe_{20}$, and $Ir_{22}Mn_{78}$, were 0.12 nm/s, 0.18 nm/s, 0.15 nm/s, and 0.12 nm/s, respectively. Uniaxial anisotropy was induced in all magnetic multilayers with Ta buffer and cover layers by a permanent magnet with a magnetic field of 350 Oe.

The tank was filled with water to a depth of 8 cm and Styrofoam was placed on its surface, where it floated. The four current-voltage terminals of the GMR-SV device were attached to the central portion of the Styrofoam; the terminals had been patterned as two cross shapes 10 mm in length and 1.0 mm in width using a metal shadow mask during thin film metallization. Fig. 2(a) shows a photograph of a real cooling system equipped with the

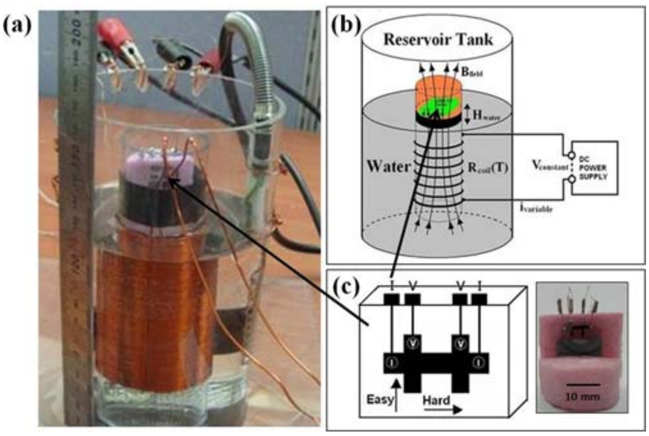

Fig. 2. (Color online) (a) A photograph of the water sensor unit and (b) a schematic of the water sensor unit with a highly sensitive GMR-SV film. The outer cylinder is the water reservoir and the inner cylinder is a solenoid, which is attached to a dc power supply. The GMR-SV film is mounted on styrofoam and left to float freely on the surface of the water, which is filled into the main acrylic chamber. A ruler is affixed to the outside of the main chamber to measure the water height. (c) A schematic and a photograph of the prototype with four probe electrodes prepared by using shadow mask during deposition of multilayer. The arrows indicate the easy and hard axes.

GMR-SV film sensor. The MR of the GMR-SV film was measured with respect to the easy axis in the linear direction, as shown in Fig. 2(c), attributed to the detection of the external field, which was varied from approximately –5 to +2 Oe in order to control the current through the coil in a constant voltage using a dc power supply.

The magnetic sensitivity (MS) of the deposited GMR -SV film sample was evaluated by plotting the MR curve, where the MR was measured using the four-terminal probing method [15]. Fig. 2(b) is a schematic showing an adjustable water level and temperature system based on the highly sensitive GMR-SV film. Fig. 2(c) shows a schematic and a real photograph of the film sample with four probe electrodes, fabricated using a shadow mask during layer deposition. Here, arrows indicate the easy and hard axes. By bonding an acrylic cylinder of 10 cm diameter and 15 cm height to an acrylic slab, a 150 cc water tank was created. Another acrylic cylinder with a diameter of 3 cm and height of 10 cm, wound 100 times with enameled wire coils of 0.8 mm diameter, was placed inside the water tank.

The sensing part of the GMR-SV film was fastened securely to the Styrofoam and placed in the inner solenoid. The electric current, which was supplied at a steady voltage, was adjusted according to the outer magnetic field determined from the MR curve obtained by measurement of the four terminals' resistance. We adjusted the water level by allowing the water in the cylinder tank exit through a 1 mm diameter hole at the center of the outer cylinder. To change the water temperature, we used a heat ray stick comprising the ceramic coating of the inside of a 220 V AC solder welding machine, as shown in Fig. 2(a). The water was first heated to 60 °C, after which it was allowed to cool to room temperature. Resistance of the submerged coil was expected to decrease with the cooling of the water, and hence, the electric current was expected to increase under the steady voltage. The increasing coil current was expected to be accompanied by an increasing magnetic field in the solenoid, thereby increasing the resistance of the GMR-SV film.

3. Results and Discussion

Fig. 3 shows two curves of major and minor MR for easy axis measured using the corning glass/Ta(5 nm)/ NiFe(8 nm)/Cu(2.5 nm)/NiFe(4 nm)/IrMn(8 nm)/Ta(5 nm) GMR-SV multilayer film, which was fabricated using a dc magnetron sputtering system. Through use of a metal mask, the easy and hard axes of magnetization were established along the width and the vertical of the fabricated device, respectively. As shown in Fig. 3(a), the

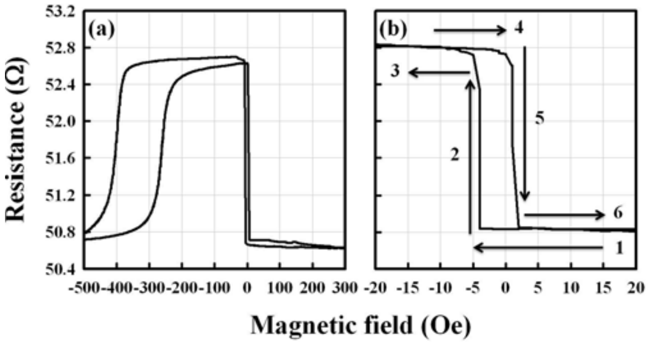

Fig. 3. Easy axis (a) major loop and (b) minor loop for the GMR-SV film, composed of corning glass/Ta(5 nm)/NiFe(8 nm)/Cu(2.5 nm)/NiFe(4 nm)/IrMn(8 nm)/Ta(5 nm) multilayers and prepared by dc magnetron sputtering. The measured MR ratio, the exchange coupling field, and the coercivity of the pinned NiFe layer were 4.1%, 320 Oe, and 65 Oe, respectively. The measured MS and the surface resistance of the linear middle point were 2.8 %/Oe and 51.8 Ω, respectively. The arrow marks the increase direction with increasing external magnetic field.

maximum MR rate of the device was 4.1% and the surface resistance of the four inner terminals was approximately 50.5 Ω. The exchange-coupling field and coercivity of the pinned ferromagnetic NiFe layer were 320 Oe and 65 Oe, respectively. The MS of the GMR-SV device for fine changes in the outer magnetic field was approximately 2.8 %/Oe up to −4 Oe.

Furthermore, measurement of the rate of magnetic resistance when an outer magnetic field was applied to the hard axis indicated a typical anisotropy magnetoresistance curve, with half the value of the magnetized easy axis MR ratio being contributed through this magnetic anisotropy effect. Using the GMR-SV water level and temperature sensor, we measured the value of surface resistance through fine changes in the outer magnetic field to determine the control properties of the device.

Fig. 3(b) shows the hysteresis curve of the minor easy axis magnetic field. The representative point of each response section is marked stage by stage in 1 → 2 → 3 → 4 → 5 → 6 order. The maximum and minimum values between the positive (+) and negative (–) in the sensitive signal of the minor loop were caused by fine changes in the outer magnetic field. Current was passed through the solenoid coil shown in Fig. 2(a) and (b) to obtain an initial field strength of +25 Oe. The constant voltage adjusted the outer magnetic field, and consequently, the field strength of +25 Oe corresponded to a surface resistance minimum of 50.6 Ω. Passing a current that resulted in an outer magnetic field of 0 Oe resulted in a negative magnetic field of nearly –4.0 Oe. When the value was decreased to –25 Oe, a maximum surface resistance value of 52.7 Ω and a MR ratio of 4.1% were obtained. When the outer magnetic field was increased back to 25 Oe, a higher surface resistance value of 51.8 Ω and outer magnetic field of +1 Oe were observed at the intermediate point, during movement from the third to fourth stages.

In the fifth stage, the MS was 2.8 %/Oe, sufficient to detect fine changes in the outer magnetic field due to the linear characteristic of the curve. Initially, minute movements of the GMR-SV device, which was placed at the center of the Styrofoam floating on the water surface, caused by the water level decrease, increased the magnetic field in the central solenoid. Since the electric current flowing through the coil was constant, the outer magnetic field in the easy axis direction of the GMR-SV film increased. Thus, the surface resistance value, as shown in Fig. 3(a), allowed the GMR-SV film to detect changes in the magnetic strength. As observed in this experiment, MS is the most sensitive, and it can thereby be easily used to detect fine changes in water level. On the other hand, when water temperature increases, the resistance of the coil increases and the voltmeter supplying the constant voltage decreases the electric current in the solenoid. This causes the magnetic field of the solenoid to decrease, and thus, the GMR-SV film, when located on a stationary water surface, detects a decrease in the outer magnetic field along the easy axis direction.

Fig. 4 plots the surface resistance values detected by the GMR-SV film. If the water temperature decreases, the GMR-SV film detects a decrease in the outer magnetic field along the easy axis and provides a plot of resistance value and MR ratio similar to Fig. 3(a) and (b), respectively. Thus, the GMR-SV device can detect fine changes in water temperature at the most sensitive position in the magnetic field. Fig. 4 shows the measured resistance values for two electrodes when a sensing current of 1 mA is passed through the other two electrodes in the water level and temperature control system. Here, the x-axis represents the water level and water temperature and the y-axis represents the resistance. Measurement of resistance was carried out using the four wire terminals of a Keithley 2400 Source Meter. As shown in Fig. 3(b), the middle point, 51.8 Ω, of a high sensitivity region of the curve is obtained by setting the external magnetic field to +2 Oe. These results were similar to the dependence of dissolving time and speed of Mg film in water on the concentration of Mg ion. That is, it seems possible that both Mg mineral sensors and cooling sensors could be developed using the current GMR-SV film [13-15].

When water height was lowered from 92 cm to 78 cm,

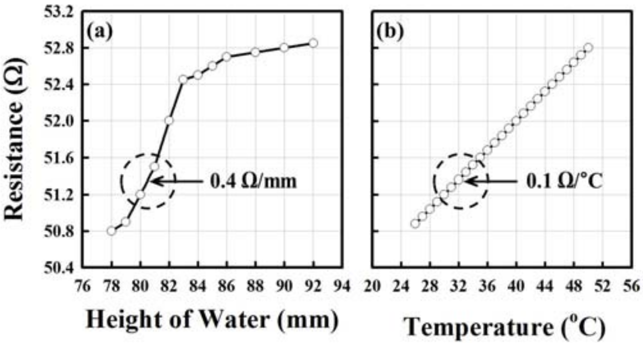

Fig. 4. Two experimental results for (a) height of water and (b) temperature of water versus resistance measured using the four-terminal probing method. Two dotted ellipses show that height and temperature sensitivity versus resistance as the water sensor has a linear region with a rate of 0.4 Ω/mm and a linear slope with a rate of 0.1 Ω/°C, respectively.

the value of magnetic resistance changed from 52.8 Ω to 50.7 Ω, as shown in Fig. 4(a). In particular, because the magnetic field away from the center of the solenoid was uneven, a linear curve was only obtained for water heights in the range of 83 cm to 79 cm. The decreasing rate of resistance per millimeter was $\Delta R/\Delta H$ = 0.4 Ω/mm. Therefore, when the sensing current is 1 mA, a change 0.4 Ω × 1 mA = 400 μV will be measured when the water level decreases by 1 mm. Thus, the sensor is suitable for application in the sensing and adjusting of water level.

On the other hand, when the water temperature was lowered from 50 °C to 26 °C, the surface resistance value changed from 53.0 Ω to 50.5 Ω, as shown in Fig. 4(b). Since the resistance changed linearly in all sections with changing water temperature, fine changes in water temperature can be measured accurately with the GMR-SV device. The decreasing rate of resistance per degree Celsius was $\Delta R/\Delta T$ = 0.1 mΩ/°C, as with the water level sensing, for a sensing current of 1 mA; therefore, a change of 0.1 Ω × 1 mA = 100 μV will be measured when the water temperature is decreased by 1 °C. Thus, the sensor is suitable for application in the sensing and adjusting of water temperature.

4. Conclusion

We fabricated a water level and temperature sensor unit based on a GMR-SV film for application in the cooling system of a potassium titanyl phosphate laser system which is used for benign prostatic hyperplasia therapy. The multilayer structure of the GMR-SV comprised corning glass/Ta(5 nm)/NiFe (8 nm)/Cu(2.5 nm)/NiFe(4 nm)/IrMn(8 nm)/Ta(5 nm). The MR ratio and MS of the GMR-SV device, which had a width of 1 mm, were 4.0%

and 2.8 %/Oe, respectively. An acrylic chamber was filled with water, and the device was mounted over Styrofoam and allowed to float freely on the water surface. A ruler was affixed to the outside of the main chamber to measure the height of water. We considered the increase in temperature for the cooling system. Although voltage remained steady during changes in power consumption and temperature, the current varied slightly. A decrease in the solenoid current indicated a decrease in magnetic field inside the solenoid. The middle point of the GMR-SV film was set in the neighborhood of the highly sensitive linear region, where the sensitivity was 2.8 %/Oe. The plot of water level versus resistance showed a linear region with a rate of 0.4 Ω/mm, whereas the plot of water temperature versus resistance showed a rate of 0.1 Ω/°C. These results indicate that the proposed sensor is suitable for application in the cooling system of KTL laser system used for treating BHP.

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