Non-Contact Current Measurement with Cobalt-Coated Microcantilevers

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Abstract

A magnetic field detection system that uses a cobalt-coated microcantilever as the detector element is demonstrated. Three different microcantilever geometries are investigated. This research also demonstrates a novel microcantilever readout technique using a dual fiber optical readout. The cantilever sensors are shown to detect changes in current as small as 0.1 A and the ability to measures current up to 5 mm from the sensor.

Key Words: MEMS, current sensor, fiber optic, microcantilever, cobalt

Introduction

Microcantilevers are key components of many Micro-Electro-Mechanical Systems (MEMS) because small changes to microcantilevers, either physically or chemically, can lead to changes in mechanical characteristics. Microcantilever research began with the development of the Atomic Force Microscope (AFM), where a microcantilever is moved across a surface, and changes in the topography lead to deflections [1]. After development of the AFM, researchers began to the use these structures as the basis of sensors to measure a variety of stimuli from chemicals to photons [2,3,4,5,6]. In the present research, we have taken these structures and used them to perform a non-contact current measurement.

As with all other non-contact current detectors, the sensor has to be sensitive to small changes in the induced magnetic field. An expression for the induced magnetic field B(I) around a long straight wire is:

$$B = \frac{\mu_o I}{2\pi R}, \quad (1)$$

where μ_o permeability of free space (H/m), I is the current (A), and R is the radial distance from the center of the wire (m). Equation 1 can easily be derived from Ampere's Law, for a path length equal to the circumference of a circle around the wire.

In order to acquire sensitivity, magnetic material must be added to the microcantilever so it will respond to small fluctuations in field. Other researchers have accomplished this by gluing magnetic particles to the surface increasing the material volume [7]. For the present research, a thin layer of cobalt is coated on the front and back surfaces of the cantilever by an ion sputtering system. Cobalt was selected because it is one of three elements that are ferromagnetic in its bulk state, and in previous testing it has been found to respond better than iron and permalloy[8].

Once a microcantilever is coated, a method to monitor its motion is needed. To detect the motion of the cantilever, we have developed a simple dual fiber probe. The dual fiber probe consists of two optical fibers placed side-by-side as close as possible to each another with one end open and the other end has optical connectors applied. The optical connectors are used to send light to the surface with the first connector, and retrieve the reflected light from the surface and channel it into an optical detector. This probe is not as sensitive to motion as some other readout techniques such as the reflective laser readout technique used in most AFM systems. But, it does have the advantage that it can be used with light emitting diodes (LED), which require fewer and simpler optics to condition the light source. Also, a cantilever may be fabricated in such a way that it can be attached to the end of a fiber to create a low profile self-contained unit. Minh et. al. demonstrated a similar hybrid system that includes a single optical fiber with a microcantilever. The microcantilever is mounted on the end, such that the motion of the cantilever is in the direction perpendicular to the fiber [9]. In our application, the cantilever and ideally the optical fiber need to be aligned with the direction of the wire. This arrangement places the cantilever so that it is perpendicular to the magnetic field, and maximizes the response. The dual-fiber-position detection system exhibits sensitivity on the order of 3 μm/mV for a blue diode laser coupled into a 200 μm fiber [10]. Increasing the amount of light delivered to the cantilever surface enhances the sensitivity. Alternatively, increasing the reflective area of the cantilever surface also aids in the sensitivity of the system.

In an effort to increase the reflective area of the cantilever, the two-legged “diving board” geometry shown in Figure 1 is used. This geometry produces a structure with a large reflective area and a low stiffness. The lower stiffness improves the sensitivity of the Microcantilever, since less force is required to make it deflect. To fabricate these structures, a silicon nitride substrate was chosen in one of two forms. The first form is a silicon nitride ledge structure that is found on the edge of a wafer of commercially available AFM cantilevers. The second form is produced by growing silicon nitride on a silicon substrate and through-etching the silicon to the silicon nitride surface thus producing a diaphragm. These substrates are then coated using an ion beam sputter coating technique. The substrate is rotated in the plume of displaced material so that both sides are coated evenly. This technique helps counter the thermal stress induced by the coating and allows thick coats to be applied without curling the substrate. The cantilevers are then patterned into the coated substrate using a focused ion milling technique [11]. The three cantilever geometries tested are shown in Figure 1. The dimensions of these cantilevers are given in Table 1. These dimensions allow evaluation of the effect of geometry on the response of the system.

Table 1 Cantilever specifications

Cantilever	Overall		Leg		Coating Thickness nm	Sensitivity A/V
	Length µm	Length µm	Length µm	Width µm		
A	145	50	50	20	150	327
B	470	270	270	20	200	0.625
C	470	200	200	30	200	23.9

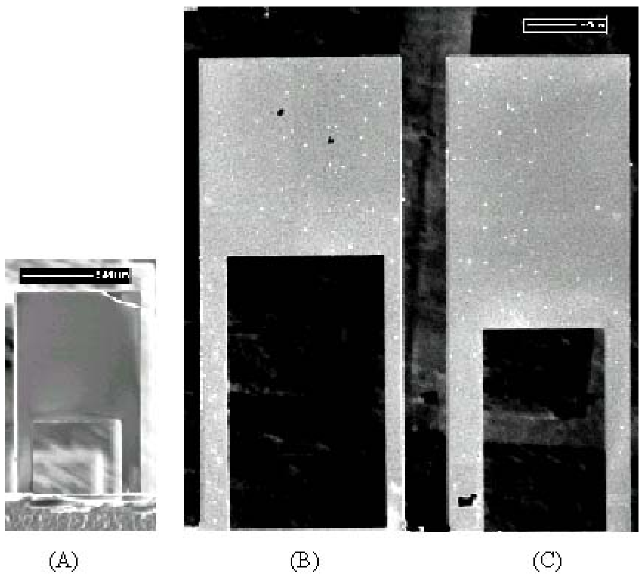

Figure 1 Cantilevers fabricated for use with dual fiber readout.

Experimental

Characterization of the cantilever response was defined by two test series. For the first test series, the root-mean-squared (rms) current driven through the wire was varied from 0 to 1.6 A. The second series of tests evaluated the effect of the wire separation distance on the response of the cantilevers. In effect, these studies evaluated the effect of the two independent variables of Equation 1. The experimental arrangement to perform these tests is shown in Figure 2. Light from either a Power Technology Inc. model LDCU12/4864 405 nm diode laser or a Ledtronics model BP280CWB1k-3.6Vf050T 450-nm LED is launched into the delivery fiber of the dual fiber. The light then strikes the cantilever and is reflected into the capture fiber and sent into a Phillips model XP2020 photomultiplier tube (PMT). The signal from the PMT is then read using a Tektronix TDS 320 oscilloscope. The current is produced in the wire by generating a sine wave in the HP 3311A function generator that is then fed into the HP 6825A bipolar power supply and the oscilloscope. The power supply then produces an adjustable current in the wire, which is mounted on a translation stage.

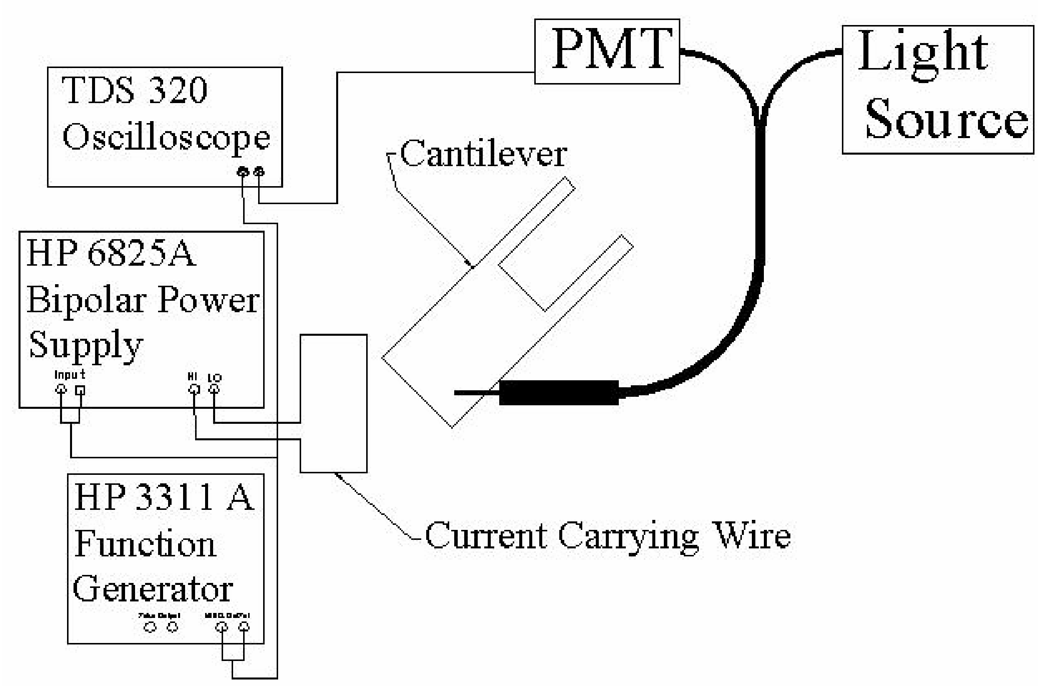

Figure 2 Experimental setup.

For the first series of tests, the rms current in the wire was adjusted from 0.2 to 1.6 A in 0.1 A increments and the 405-nm diode laser was used as the light source. An example of a typical input pulse and the response from the PMT is shown in Figure 3. A comparison of the amplitude of the response of the three cantilevers tested is shown in Figure 4. The amplitude as a function of current was normalized by dividing the value at each point by the amplitude at 1.6 A for each curve. As can be seen the curves for cantilevers B and C have a linear shape that follows the magnetic field defined in Equation 1. Cantilever A also has a region were the response follows the magnetic field for currents above 1.1 A. It is likely that cantilever A does not follow the magnetic field below 1.1 A because of a combination of effects. First, cantilever A is much shorter than cantilevers B and C and therefore has a higher stiffness, making it less sensitive to change in the magnetic field. Second, the reflective area of cantilever A is considerably smaller than that of cantilevers B and C, meaning that much of the incoming light is not reflected to the capture fiber, and thus the sensitivity of the dual fiber is reduced. Cantilever A's divergence in response from the magnetic field is not the only noteworthy result of these tests. The curves for the three cantilevers have very different sensitivities, which have been obscured by the normalization. The three cantilevers have sensitivities that range from 0.625 to 327 A/V. As can be seen in Table 1, cantilever B, which has the longest legs and the widest head, has the greatest sensitivity. This makes sense, because the longer legs allow for a smaller stiffness, which means that less force is needed to deflect the cantilever. This also allows the cantilever to have greater deflections. The larger reflective area also allows for more incoming light to be intercepted from the delivery fiber and thus increase the response signal. The larger reflective area also allows for more volume of the magnetic material to react to fluctuations in the magnetic field.

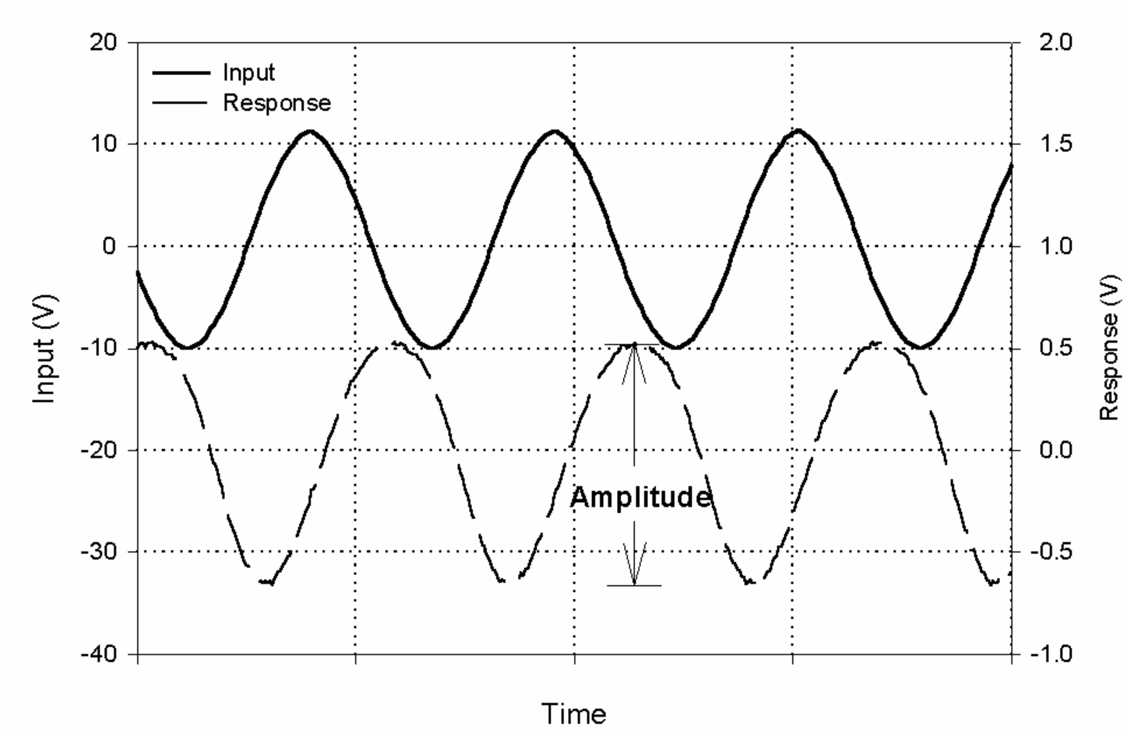

Figure 3 Typical input signal and response.

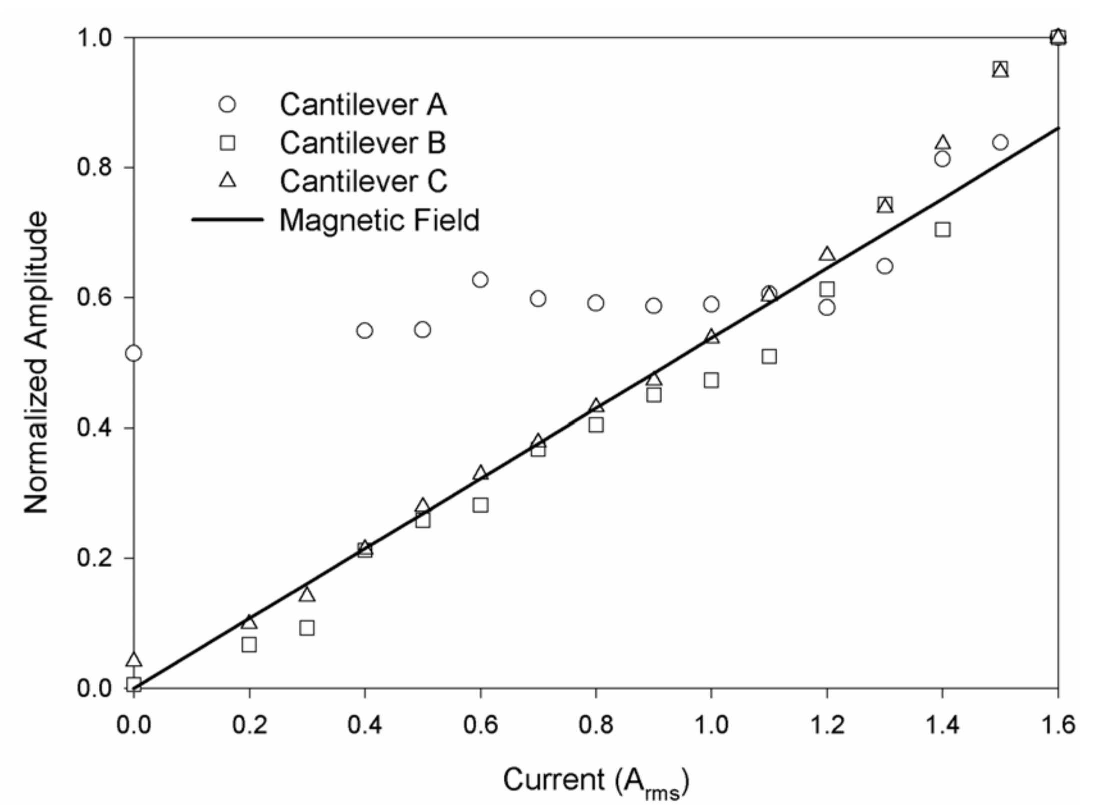

Figure 4 Effect of variation in current on the response of cantilever sensor.

Next we evaluated the effect of wire separation distance on the response of the cantilevers. These tests were once again performed using the 405-nm diode laser and a current of 1.2 A. Dividing the value at each point by the amplitude when the wire was at the initial position for each curve normalized the amplitudes of the response. The three cantilevers had similar shaped responses, although they each have different maximum working distances as can be seen in Figure 5. Cantilever B most closely followed the magnetic field out to 2 mm from the surface. Cantilever C showed the greatest ability to follow the magnetic field for the longest distance, and C was able to follow the field out to 5 mm from the surface. Cantilever A followed the magnetic field out to only 0.2 mm from the surface before the noise in the system overwhelmed the signal and is not shown in Figure 5. This is not surprising, since the cantilever has a considerably smaller reflective area and the sensitivity was very low. It is interesting to note that the cantilever that responds to magnetic field at the greatest distance is not the most sensitive.

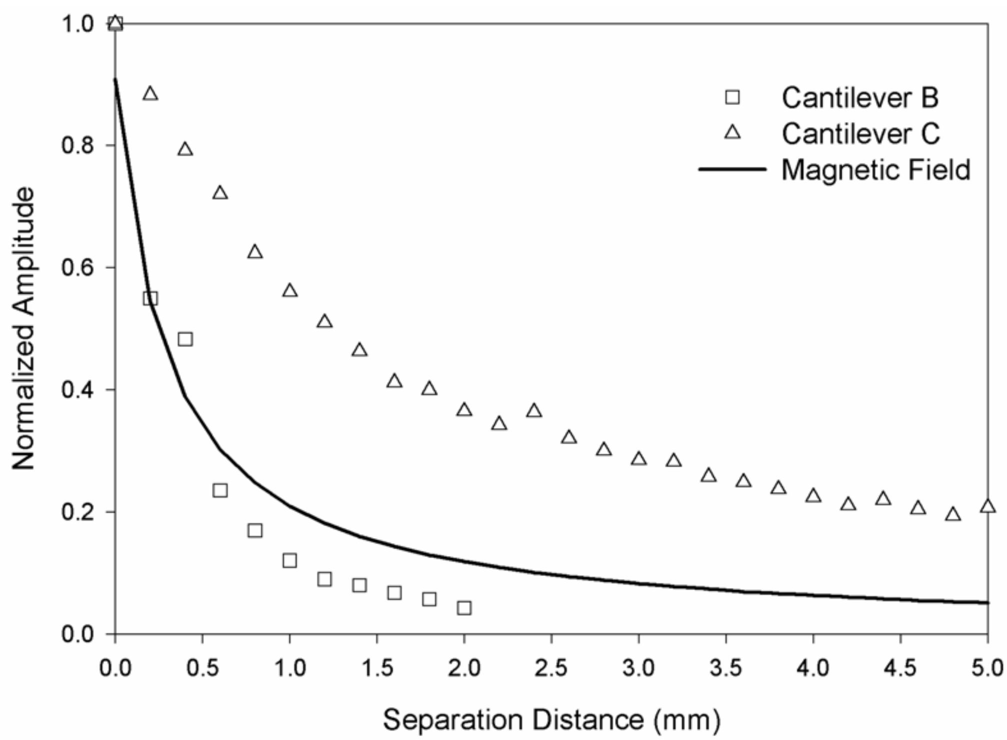

Figure 5 Effect of wire separation distance.

While the tests described above were performed with a diode laser light source, many of these tests could have been performed using a LED instead. To demonstrate this cantilever B was driven by a 1 A signal and was interrogated with both a LED and a Diode Laser light source. The response of Cantilever B had an amplitude of 1.2 V when interrogated with the diode laser. For the same parameters, the amplitude of the response of Cantilever B was 7.5 mV when interrogated with a LED. It can easily be seen that the increased light from the laser allows for higher response amplitude, and thus a better signal to noise ratio. It should also be noted that, although the signal with the LED is three orders of magnitude smaller it is still clearly discernable. It should be stated that, brighter LEDs are available, than the one used in this effort. Also, better fiber-to-LED coupling methods need to be explored.

Conclusions

This research gives preliminary results that illustrate the feasibility of a hybrid fiber-optic non-contact current sensor. The research evaluated both the micromechanical and the fiber-optic portion of the sensor. Two major conclusions could be reached for the micromechanical portion. First, the amplitude of the response was a function of the current for all of the cantilevers for at least part of the range of currents tested. Cantilevers B and C managed to follow the current for the entire range. Second, cantilevers B and C also followed the magnetic field as a function of wire separation distance. This means that the cantilevers are detecting changes in the magnetic field and could be made to function as a non-contact current sensor. This research also gave a good understanding of the interaction of the cantilevers with the dual-fiber probe. First, it was found that the diameter and numerical aperture of the fiber determine the reflective area of the cantilever. As these variables increase, more reflective area is needed to capture the incident light from the dual-fiber probe. The second result is more obvious, increasing the light delivered increases the signal to noise ratio. This can be easily accomplished by either using a brighter light source, such as a laser, or increasing the optical fiber diameter. Finally, the response of all but Cantilever A could be detected using an LED instead of the laser, thus potentially reducing the cost of the sensor. Our results not only demonstrate the feasibility of such a sensor, but also provide an empirical basis, and an obtainable benchmark for similar approaches.

Acknowledgments

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