Determination of Surface Temperature on Micrometer Scaled Objects

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ABSTRACT

Piezoresistive cantilevers hold great potential as magnetic field sensors. In an eventual application, a cantilever placed near a conductor will deflect due to the magnetic field induced by the conductor's current. A resistance change also accompanies this deflection. Resistance, and hence deflection, may be measured via a simple Wheatstone bridge circuit. Described here are tests and results aimed at developing such microcantilevers as Micro Electro Mechanical Systems (MEMS) devices for magnetic field and electrical current sensing. The emphasis in the present description is characterization of the cantilever response for different bias currents. It has been established that bias current at sufficient levels will heat the cantilever. As the bias current is raised above a certain value, defined by the geometry of the cantilever, the cantilever glows brightly. Two effects of this heating on the cantilever are a decrease in resonant frequency and an increase in the amplitude at that resonant frequency. For bias current below the value, which causes the cantilever to glow, the peak amplitude values increases by about 20 % while the resonant frequency decreases from 34.5 kHz to 34.1 kHz. To better characterize this effect, a piezolever was fabricated to measure the temperature by the thermographic phosphor method. This temperature rise can be quite substantial. For example a current of about 5 mA leads to a temperature of about 500 °C on an as-received non-contact piezolever coated with thermographic phosphor. The ability to measure temperature transients caused by short-pulse heating was also demonstrated. Future tests will utilize a phosphor with a sufficient range to diagnose temperature for a 10 mA bias. At this current the cantilever glows brightly, like the filament of a light bulb. No immediate deleterious effects due to these high temperatures on the cantilever are apparent.

INTRODUCTION

Piezoresistive cantilevers hold great potential as current and magnetic field sensors. By Faraday's Law, the current conveyed by any conductor will produce a magnetic field that is proportional to current. In the present application, the deflection of the cantilever is caused by such a magnetic field. In turn, a resistance change results from the deflection. A simple Wheatstone bridge circuit measures this resistance, and therefore, current or magnetic field. In the process of determining the magnetically induced deflection, a bias current must be applied across the piezolever to determine the change in resistance. It was noted in some early tests that there is a slight change in response of a biased and unbiased piezolever. These observations led to the investigation of the effect of bias current on the response of the piezolever. It was determined that increases in the bias current tend to increase the maximum deflection at the resonant frequency while at the same time reducing the frequency at which the piezolever resonates. These changes can be explained by the fact that flowing current though this structure causes it to heat. As the temperature increases, the stiffness of the structure is reduced, allowing for the increased deflection and reduced resonant frequency. These results led to another interesting question: how hot does the microcantilever structure become due to the applied bias current? Bias currents as low as 10 mA cause the cantilever structure to glow like a light bulb filament. There are few temperature measurement techniques that are capable of measuring the surface temperature of an object on the micron scale. It was obvious that a non-contact temperature measurement is necessary since the contact area is so small and any contact made with the surface may dissipate the heat too quickly for an accurate measurement to be made. One technique that shows promise and which is demonstrated here is phosphor thermography. A laser or light-emitting diode produces fluorescence from a rare earth doped phosphor coated onto the cantilever. The characteristic decay time of the fluorescence is a well-behaved function of temperature and is therefore a reliable temperature indicator (1).

PHOSPHOR COATING AND CALIBRATION

To prepare for temperature measurement, an unmodified piezoresistive cantilever was coated with a thermographic phosphor. The phosphor chosen was magnesium fluorogermanate doped with manganese (Mg_4FGeO_6:Mn). This phosphor was chosen for its wide temperature range and wealth of previous experience. To coat the piezolever, it was first dipped into Sperex 115 high temperature paint, a material often used as a bonding agent for phosphors (2). The piezolever was then mounted onto a precision adjustable stage and translated towards a pile of the Mg_4FGeO_6:Mn phosphor. As the piezolever approached the sample of phosphor powder, electrostatic charge caused phosphor particles to attach to the surface. The coated piezolever is shown in Figure 1.

FIGURE 1 PHOSPHOR COATED PIEZOLEVER

A calibration curve is a plot of phosphor decay time versus temperature. The temperature response of a phosphor can vary from one batch to another so it is always wise to perform a calibration of the specific material to be used. For this, the phosphor is placed onto a temperature-controlled heating element (commonly used for diffusion-pump heating). The temperature is determined by a type K thermocouple and is controlled by a variac. A digital oscilloscope captures and displays the fluorescence amplitude versus time. A LabView program residing on a laptop computer downloads this data from the oscilloscope and calculates decay time. The process is repeated for increasing temperatures and the variation in temperature is plotted as a function of the decay time. The plot shown in Figure 2 is broken into two regions and a curve fitting routine was used to determine the mathematical relation between the decay time and the temperature.

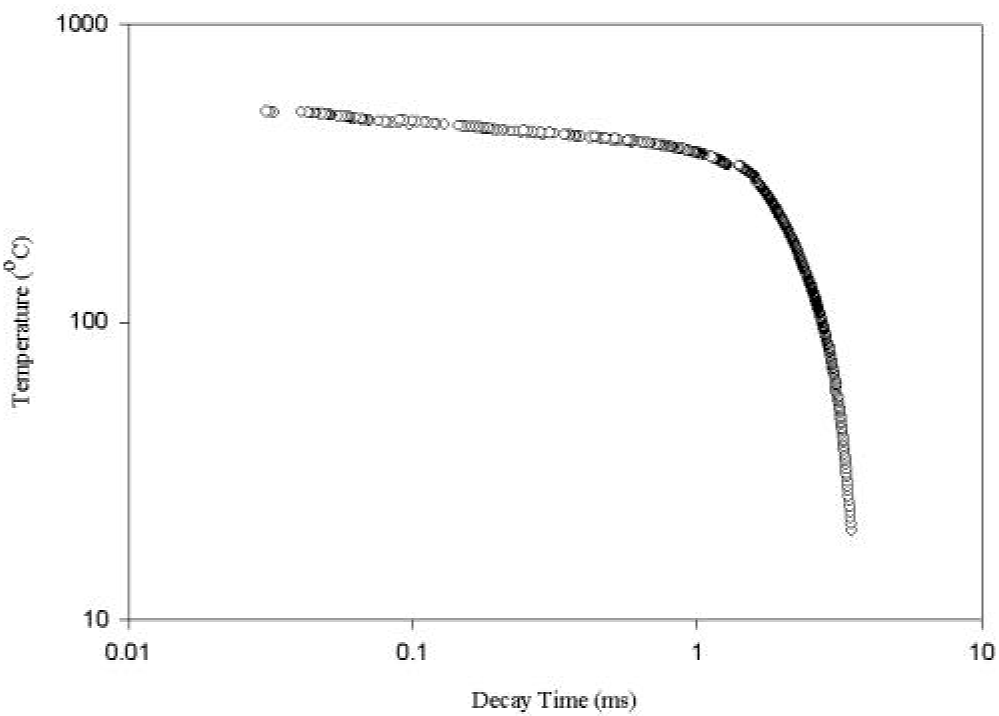

FIGURE 2 CALIBRATION CURVE

EXPERIMENTAL SETUP

The phosphor deposited on the cantilever is excited using a Laser Science Inc. VSL-337 NDS nitrogen laser (wavelength of 337 nm and 3ns pulse duration) directed at the surface using one fiber of a specially fabricated 200-micron dual core fiber. This dual core fiber was originally designed to determine the motion of microcantilevers with a much smaller reflective area (3). The laser light strikes the surface and induces the fluorescence that is captured by the second fiber and directed through a 650 nm optical filter onto the photocathode of a Hamamatsu Photomultiplier Tube (PMT), model H5783-01. The sync output of the nitrogen laser is used to trigger the Tectronics TDS 460 A Oscilloscope to capture the decay trace from which the decay time is calculated. The decay signal is then compared to a calibration curve to determine the surface temperature. A Keithley 236 Source Measure unit is used to provide a constant bias current to piezolever and to measure the voltage across the piezolever. A digital camera with a microscope lens system is used to monitor the condition of the piezolever with the increasing bias current. A schematic of the experimental arrangement is shown in Figure 3.

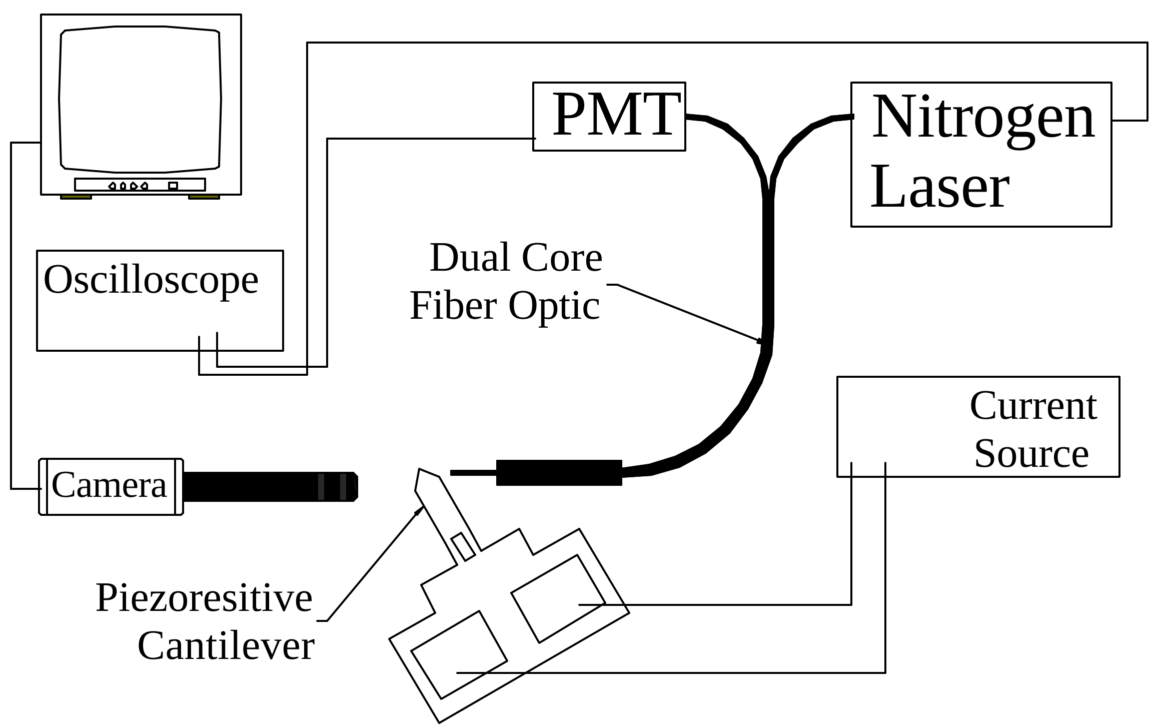

FIGURE 3 SCHEMATIC OF EXPERIMENT

RESULTS

RESONANT FREQUENCY AND DEFLECTION VERSUS BIAS CURRENT

As noted above, while testing the response of piezoresistive cantilevers to changes in magnetic field, it was found that the application of a bias current to the piezoresistive cantilever changed the response of the cantilever. This discovery led to a series of tests to better understand the phenomenon. An increasing amount of bias current was applied to the cantilever and the motion detected using an optical beam deflection technique. As the bias current was increased, the resonant frequency decreased while the amplitude increased. Also, once the bias current reaches a certain level, the legs of the piezoresistive cantilever began to glow like a light bulb filament. A typical example of this trend is shown in Figure 4. Figure 4 also shows an image of the modified piezoresistive cantilever used in these tests. The cantilever was modified using an FEI FIB 200 focused ion beam milling system. Two modifications were made. First, a hundred square micron hole was drilled at the bottom of the cantilever head to create a resistive bridge and to determine the sputter rate of the cantilever material. Next the legs of the cantilever were thinned to lower the resonant frequency. The graph in Figure 4 shows another interesting trend; once the bias current reached the glow point, the resonant frequency begins to increase again, while the amplitude continues to increase. The decrease in the resonant frequency and increase in amplitude can be easily explained as a heating effect. As more current is conducted through the cantilever, the temperature increases. The increase in temperature leads to a softening of the cantilever, thus reducing the stiffness and the resonant frequency. This also explains the increase in the amplitude since the reduced stiffness allows for increased motion of the cantilever. While a general hypothesis had been made, the relationship between the temperature of the cantilever and the bias current was still unknown.

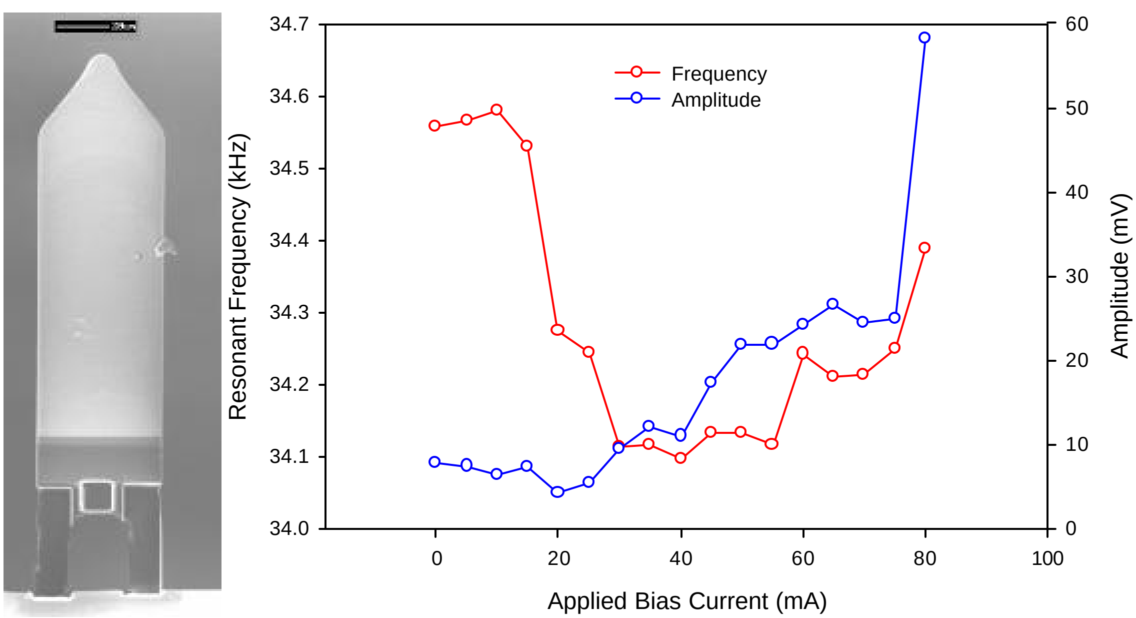

FIGURE 4 VARIATION IN RESONANT FREQUENCY

TEMPERATURE MEASUREMENT

To better understand the relationship between applied bias current and temperature, a piezolever was coated with thermographic phosphor as described above. The coated piezolever reached the glow point at 6 mA, nearly a quarter of the 40 mA applied bias current of the modified piezolever shown in Figure 4. This point defined the upper bias current limit. From this point, several tests were run using 1 mA increments in the applied bias current. These tests showed that the temperature at the tip of the piezolever consistently reached a plateau with an applied bias current between 4 and 5 mA. This trend was repeatable. Therefore, the relationship between the bias current and the temperature for these lower currents was investigated in more detail. The test series was performed with a 0.2 mA increment from 0 to 5 mA. The results are shown in Figure 5. As can be seen, the temperature grows exponentially from 0 to 2 mA and then begins more gradual increase in temperature until 4 mA where temperature appears to level out. In an attempt to better understand relationship between the bias current and the temperature change, the Ohmic heating value were calculated and plotted in Figure 5. These heating values are directly related to temperature of the piezolever. The curve for the Ohmic heating values closely follows the temperature curve for values up to 2 mA. At this point, there is a change in the slope of both curves with an increasing separation between them with increasing bias currents. This effect could be attributed to one of three things. Either the piezolever was being cooled by some convection and/or conduction, or the phosphor no longer follows the temperature due to insufficient thermal contact, or the temperature of the surface has reached a value that exceeds the range of the phosphor. Further testing is planned with phosphor that has a larger temperature range. In addition, use of phosphor with smaller particle size and a more uniform coating on the cantilever is desirable and will be pursued.

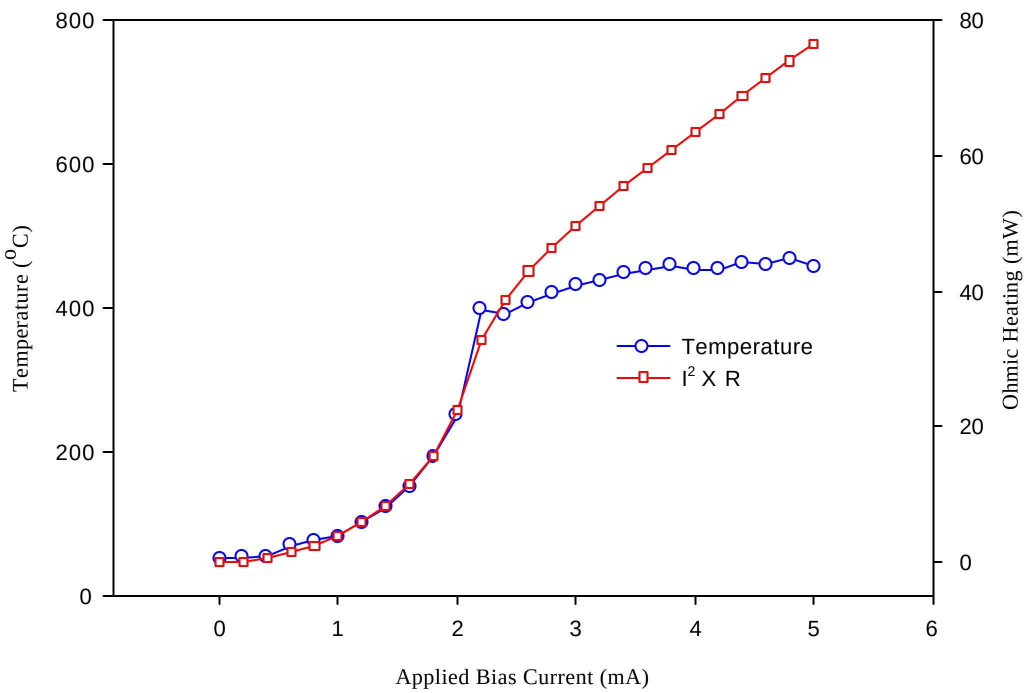

FIGURE 5 VARIATION OF TEMPERATURE

Once the temperature limits of the phosphor had been determined, the next question to be investigated concerned how long it takes the piezoresistive cantilever to reach thermal equilibrium with the environment. To test the feasibility for answering this question, a transient experiment was devised. For this, a 9 V pulse 10 ms wide, termed a "heating" pulse, is used to bias the piezoresistive cantilever at a frequency of 40 Hz (the minimum rate for this particular pulser). This pulser was made in house and is designated Pulser 1 in schematic shown in Figure 6. The delay time, ϕ_{Heat}, between a clock pulse from this unit and the heating pulse may be adjusted. A second pulser, a Racal Dana Model 25 is triggered by the clock pulse from Pulser 1. Subsequently, it in turn triggers the laser and oscilloscope. The second pulser allows for the delay, ϕ_{Laser}, to be controlled between the time the laser is fired and when the heating pulse is sent to the cantilever. This allows the temperature to be measured at multiple points in time relative to the heating pulse. The maximum pulse repetition rate of the laser is 30 pulses per second. Thus a 1/n Generator is used which only outputs 1/n times the input rate. It accepts the clock signal from Pulser 1 and outputs pulses to the Racal Dana unit that triggers the laser. By selecting the n = 2 setting of the 1/n Generator, the laser fires at 20 times per second and does not exceed that value. The relation between the clock pulse, laser trigger pulse, fluorescence signal, and heating pulse are all depicted in Figure 7.

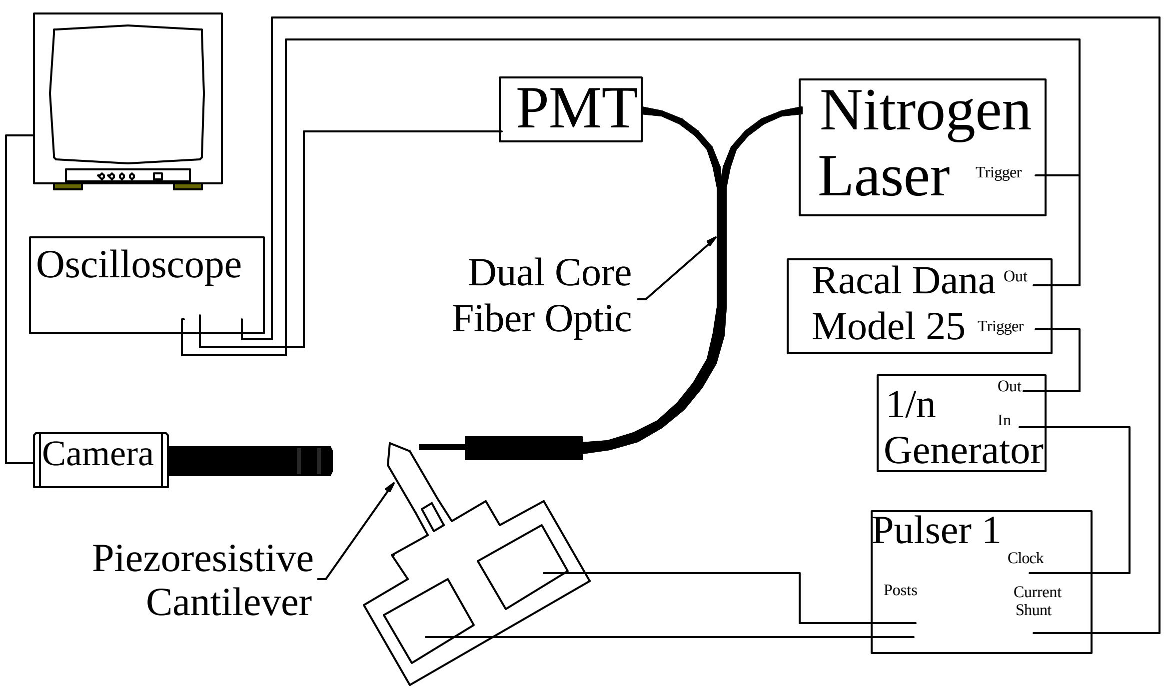

FIGURE 6 SETUP FOR TRANSIENT TESTS

The particular phosphor used for these first experiments was selected because of its wide temperature range and efficiency. Another perceived advantage is that it can be excited with a blue light emitting diode (LED). In fact, LED-excited fluorescence was detectable using the LED instead of the laser. However, its characteristic long decay time limited the time resolution of this transient experiment. Nonetheless, it is clearly demonstrated that transient measurements are feasible.

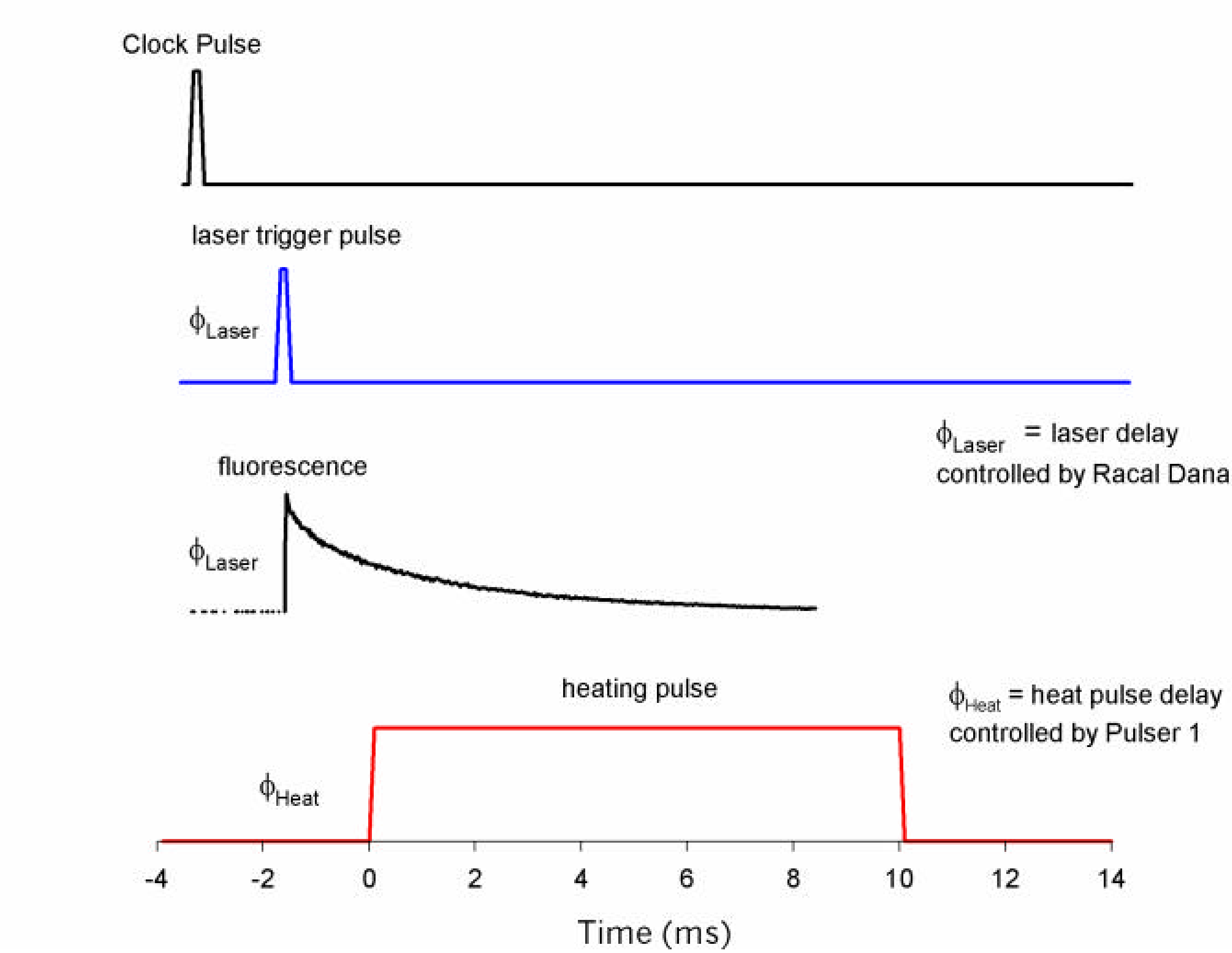

FIGURE 7 TIMING SCHEMATIC

Figure 8 shows some of the transient temperature measurement results. There are two temperature traces shown, corresponding to two different load resistors, of 10 kΩ (green) and 2.2 kΩ (blue), used with the photomultiplier. With higher impedance the signal strength is higher, but the response time is reduced. As can be seen in Figure 8, the change in the impedance does not significantly affect the values of the temperature measurement within the temperature resolution of this setup and phosphor. Figure 8 also shows that the temperature appears to begin to increase 3 ms before the initiation of the bias pulse, and decrease 3 ms before termination. This seems puzzling until the decay time of the phosphor is considered. As seen in Figure 7 above, the fluorescence, though initiated prior to the heat pulse, may still be emitting when the heat pulse arrives. Since the temperature measurement is not exactly instantaneous, the time lag allows for heating/cooling of the surface near the edges of the heating pulse, thus affecting the temperature measurement in the regions where the decay signal overlaps the edges of the heating pulse. Figure 9 illustrates this with two fluorescence signals for which the heat pulse occurs 6 ms (blue) and 1 ms (red), respectively, after the fluorescence begins. The latter signal is identical to the first until after the arrival of the heating pulse. At this point its decay rate or amplitude drops more rapidly, indicating a higher temperature.

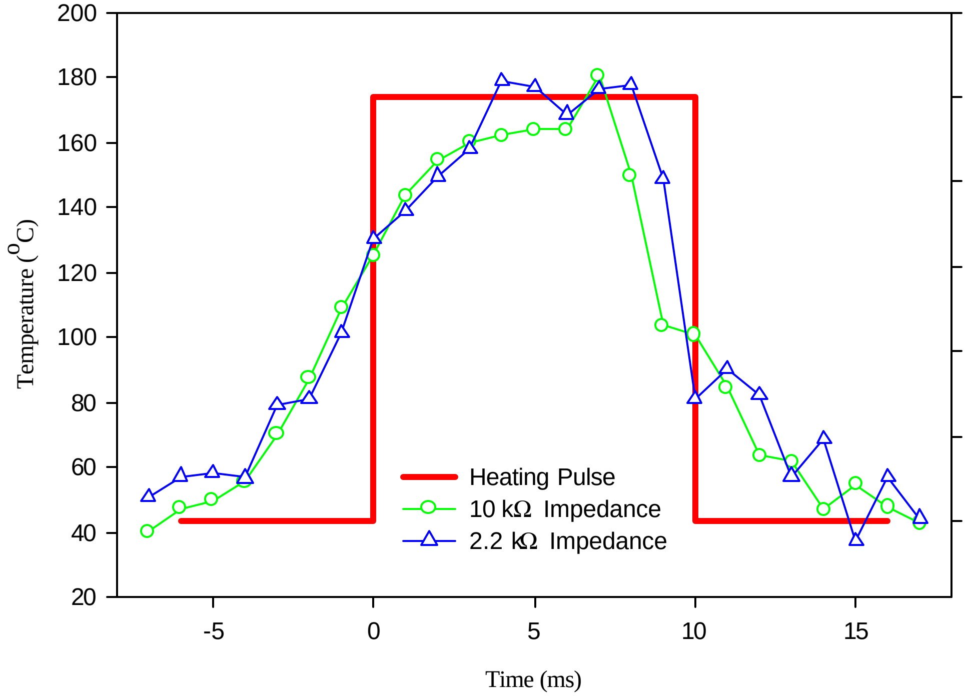

FIGURE 8 TRANSIENT TEMPERATURE OF PIEZOLEVER WITH PULSED BIAS CURRENT

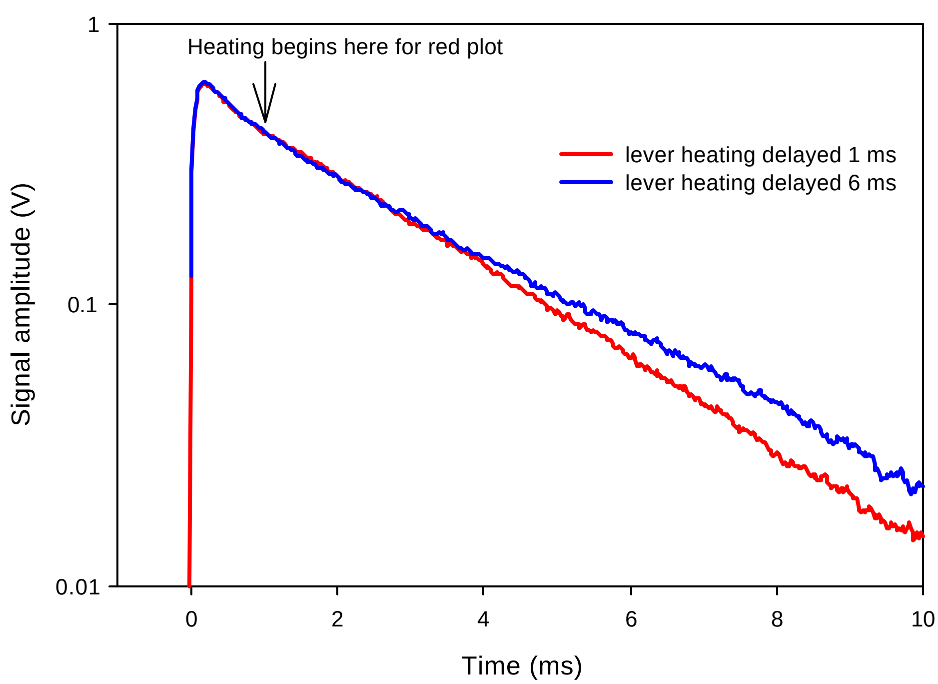

FIGURE 9 COMPARISON OF FLUORESCENCE SIGNALS HEATED AT DIFFERENT TIMES

CONCLUSIONS AND DISCUSSION

The ability of the phosphor method to sample the temperature of a cantilever on a micro-scale has been demonstrated. It has also been shown that a uniform coating of phosphor is not required to measure the temperature. Results have also shown that Mg_4FGeO_6:Mn functions well at bias currents below 2 mA and reasonably well between 2 and 4 mA, ie, up to about 500 °C. For future investigations, shorter decay time phosphors may be used. The shorter decay time would also increase the time resolution of the transient method. Several oxysulfide phosphors doped with europium or praseodymium exhibit high temperature sensitivity with a decay time of ten microseconds or less. At moderately high temperatures, say above 500 °C, oxide, YAG or vanadate phosphors may be useful. There is; however, a tradeoff between decay time and range of sensitivity, the shorter decay time phosphors cover a smaller temperature range. Thus, future work will likely involve a number of phosphor coatings to cover various possible temperature ranges and situations. The results of this effort may have implications not only for magnetic and current detection, but also for sensors based upon temperature-modulation methods. (4)

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