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Silicon-Etalon Fiber-Optic Temperature Sensor

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SILICON-ETALON FIBER-OPTIC TEMPERATURE SENSOR

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SUMMARY

A temperature sensor is described which consists of a silicon etalon that is sputtered directly onto the end of an optical fiber. A two-layer protective cap structure is used to improve the sensor's long-term stability. The sensor's output is wavelength encoded to provide a high degree of immunity from cable and connector effects. This sensor is extremely compact and potentially inexpensive.

INTRODUCTION

Considerable research has been performed to develop an accurate, compact and inexpensive fiber-optic temperature sensor. The principle advantages of fiber-optic sensors are immunity to electrical interference, small size, light weight, intrinsic safety, and chemical inertness. A disadvantage of fiber-optic sensors is the high variability of the fiber link's transmissivity, which necessitates the use of information encoding schemes that are signal-level insensitive.

Fabry-Perot etalons are a particularly promising type of temperature sensor because the measurement information is wavelength encoded and is therefore highly resistant to degradation due to changes in the properties of the fiber-optic components (refs. 1 to 6). An etalon's reflectance is a minimum at each of its resonant wavelengths, which, for an uncoated solid etalon, are given by $2nd/m$, where n is the etalon's refractive index, d is its thickness, and m is an integer. Temperature can be sensed using an etalon constructed of a material, such as silicon, whose refractive index is a strong function of temperature. The positions of the minima in the etalon's spectral reflectance can then serve as a sensitive temperature indicator.

A Fabry-Perot etalon made from an approximately 1-μm thick piece of single-crystal silicon is used in a commercial fiber-optic temperature sensor (ref. 4). Manufacture of this type of sensor requires that relatively thick silicon wafers be etched to the desired thickness and then bonded to the end of an optical fiber. By sputtering a silicon film directly onto the fiber end, reduced cost, smaller size and greater ruggedness may be obtained. Schultheis, et al., have described a sensor that consisted of a sputtered silicon film which was protected by a polyimide coating (ref. 6). This paper describes a sensor that uses a two-layer sputtered cap structure which provides greater stability than can be obtained when an organic coating is used.

SENSOR DESCRIPTION

A critical issue in the development of a practical sputtered-film temperature sensor is its long-term stability. Due to changes in its physical structure, the silicon film's optical properties can be expected to change after exposure to elevated temperatures. A silicon-film temperature sensor would need to be annealed, prior to use, at a temperature significantly higher than the maximum temperature it will encounter in service.

A practical silicon-film temperature sensor also requires some type of protective coating on its exterior surface. This protective cap structure should provide reasonably high reflectivity and at the same time block out any stray light. To prevent long term drift due to chemical reactions, the sensor structure must be highly stable; at the maximum temperature to which the sensor will be exposed, the protective cap material(s) should not appreciably react with or diffuse into the underlying silicon. The protective cap should also block external reactants; in particular, it should act as barrier to oxygen in order to prevent oxidation of the silicon.

Figure 1 shows, schematically, our temperature sensor, which has the following three-film structure:

(1) 1.4-μm silicon,
(2) 0.14-μm silicon dioxide,
(3) 1-μm FeCrAl (77.5:10.6:11.9, by weight).

The intermediate oxide layer is intended to prevent the constituents of the outer metal film from diffusing into the silicon and irreversibly altering its refractive index. The oxide film's thickness is chosen to be 1/4-wave at the sensor's design wavelength of 850 nm. This causes the reflections from the silicon-oxide and oxide-metal interfaces to interfere constructively, thereby maximizing the amount of light reflected back through the silicon film. FeCrAl, like stainless steel, forms a protective scale on exposure to an oxidizing ambient, and is therefore expected to act as a barrier to oxygen to prevent oxidation of the underlying silicon.

This sensor was fabricated by sputtering onto the ends of step-index multimode fibers having 100-μm core diameters and 140-μm cladding diameters. These fibers have an approximately 10-μm thick polyimide buffer coating which protects the fiber surface. This buffer material permits these fibers to be exposed to temperatures as high as 350 °C. In order to measure temperatures higher than 350 °C, fibers with gold buffer layers can be used (to 650 °C), however, these fibers are expensive.

The fiber ends were prepared for sputtering by first removing the buffer material from the last 1 in. of a 1-m long piece of fiber. The polyimide buffer was first turned to ash using a butane flame, then the ash was wiped off using a methanol-soaked wipe. The fiber was cleaved approximately 1 mm from the end of the remaining buffer material, and the cleaved ends were then inspected for smoothness and cleanliness using a microscope. Prior to insertion in the sputtering system, the fibers and their holder were ultrasonically cleaned using deionized water and detergent, then rinsed under running deionized water, and finally blown dry with nitrogen.

The films were deposited in an RF sputtering system having three 6-in. diameter targets. A fiber holder was used to hold the fiber ends perpendicular to the target. Without breaking vacuum, all three films were sputtered at a power level of 200 W. The silicon and FeCrAl were sputtered in argon, while the oxide was sputtered in an 80:20 mixture of argon and oxygen. The fibers were then spliced to fused-fiber couplers, as shown in figure 1, so that the reflectivity of the sputtered films could be monitored.

EXPERIMENTAL RESULTS

Figure 2 shows the sensor's spectral transmissivity which was measured, at room temperature, immediately after fabrication and again after the sensor was annealed for 19 hr at 310 °C. As shown by the data plotted in figure 2, annealing has the effect of reducing the silicon film's absorption coefficient and refractive index. Figure 3 shows the transmissivity of the annealed sensor at 25, 125 and 230 °C (changes in transmissivity from the previous figure are caused by the use of different fibers and connectors). As shown by figure 3, increasing the sensor's temperature increases the silicon film's refractive index, thereby shifting the minima in the sensor's spectral transmissivity to longer wavelengths.

In order to assess the stability of this sensor, its transmissivity was monitored over the course of a 700-hr long exposure to a temperature of 230 °C. Figure 4 shows, as a function of time, the position of one of the minima in the sensor's spectral transmissivity. The observed variations in the resonant wavelength were determined to be caused by instabilities in our measurement apparatus. More accurate measurements need to be performed before the long-term stability of this sensor can be determined.

This temperature sensor is intended to be used in conjunction with an LED source and a micro-optic spectrometer (ref. 3). The spectrometer uses a 2400 line/mm prism grating and a 5-mm diameter GRIN lens to disperse the sensor's output spectrum across a 12-element photodiode array. The array's active elements have a width of 80 μm and a center-to-center spacing of 140 μm. The spectrometer's channel separation is 7.2 nm and each channel's width (FWHM) is 12.4 nm. This type of spectrometer permits the development of a compact multi-channel sensor system in which one spectrometer analyzes the outputs from a number of different kinds of spectrum-modulating fiber-optic sensors (ref. 3).

Figure 5 shows the sensor's input and output spectra when an LED source is used. Figure 6 shows the spectrum from the LED-powered sensor that is incident on each of eight spectrometer channels. These data show that the micro-optic spectrometer has sufficient resolution to analyze the sensor's output.

A simple method of determining the sensed temperature is to use the ratio of the outputs from two channels. Figure 7 shows the ratio of the channel 3 and 5 outputs as a function of temperature. Alternatively, a more sophisticated signal processing method, which uses the outputs from all the channels, might be used (ref. 1). Such an approach may be able to compensate for changes in the LED spectrum, eliminating the need for precise control of the LED's temperature and permitting aged LEDs to be readily replaced.

CONCLUDING REMARKS

The three-film sensor structure described here has been shown promising, however, its long-term stability has not yet been determined. Considerable work also needs to be performed to develop the electronic hardware and signal processing software that are needed to produce a practical instrument.

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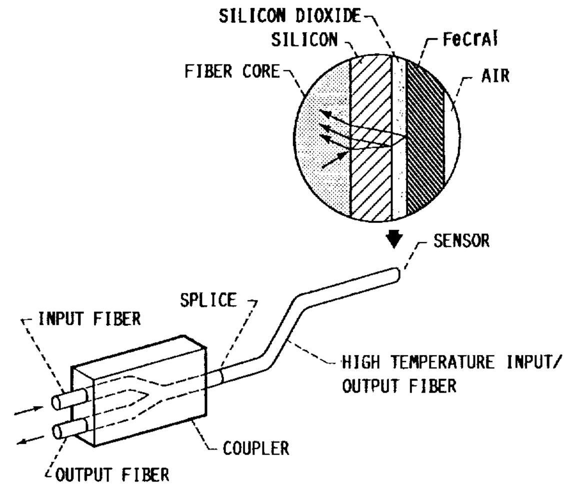

FIGURE 1. - THIN-FILM TEMPERATURE SENSOR.

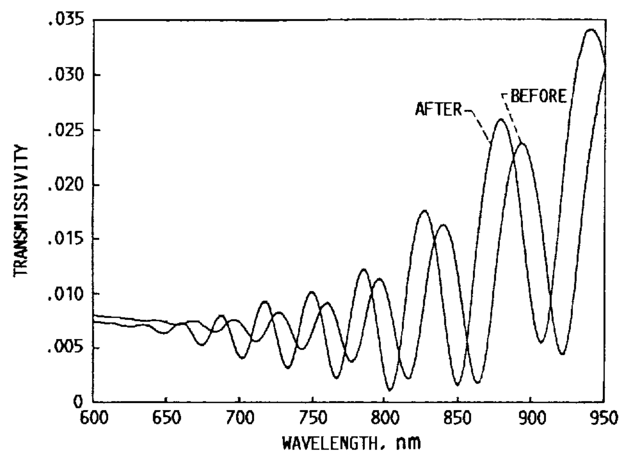

FIGURE 2. - TRANSMISSIVITY BEFORE AND AFTER ANNEALING.

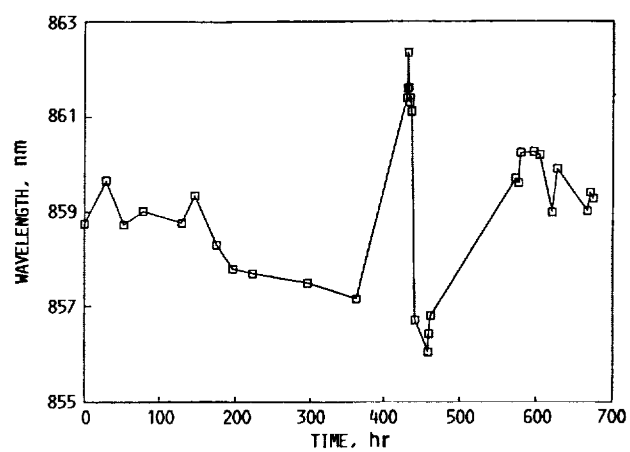

FIGURE 4. - RESONANT WAVELENGTH VERSUS TIME AT 230 °C.

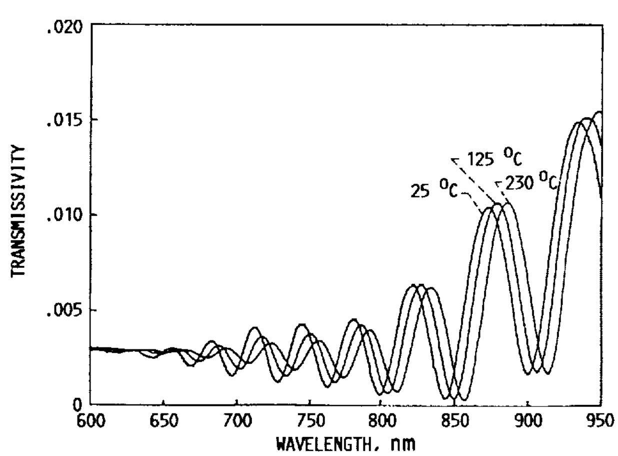

FIGURE 3. - TRANSMISSIVITY AT 25, 125, AND 230 °C.

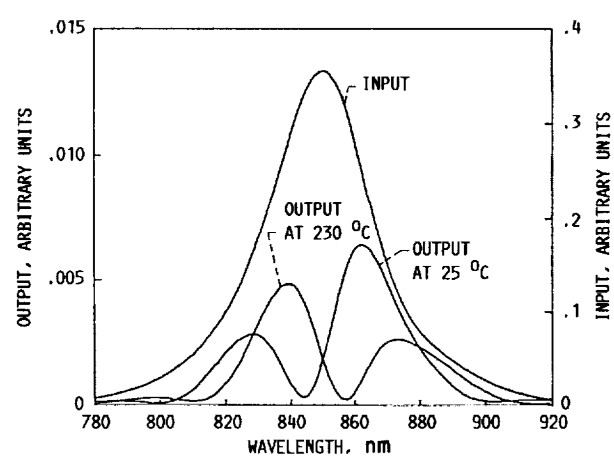

FIGURE 5. - SENSOR INPUT AND OUTPUT SPECTRA.

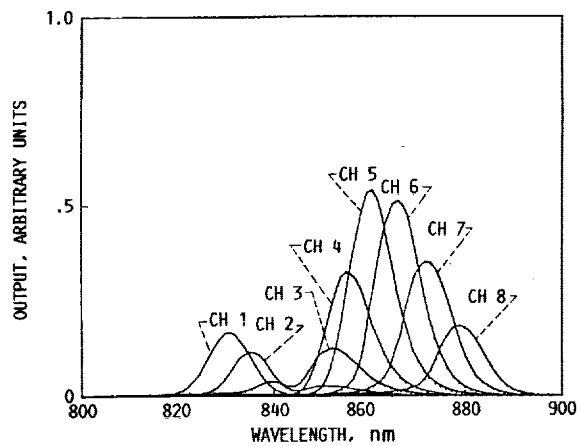

FIGURE 6. - SPECTRA INCIDENT ON EACH PHOTODIODE ARRAY ELEMENT.

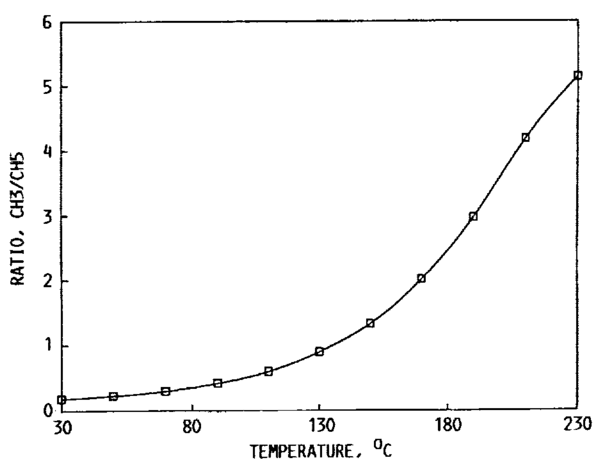

FIGURE 7. - RATIO OF CHANNEL 3 AND 5 OUTPUTS VERSUS TEMPERATURE.

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