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George et al.

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(54) **SILICON MICROMACHINED BROAD BAND LIGHT SOURCE**

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Related U.S. Application Data

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(51) **Int. Cl.**^{7} **H01J 9/24**; H01L 21/00

(52) **U.S. Cl.** **445/23**; 438/50

(58) **Field of Search** 445/23–25; 438/50, 438/456, 745, 52, 53

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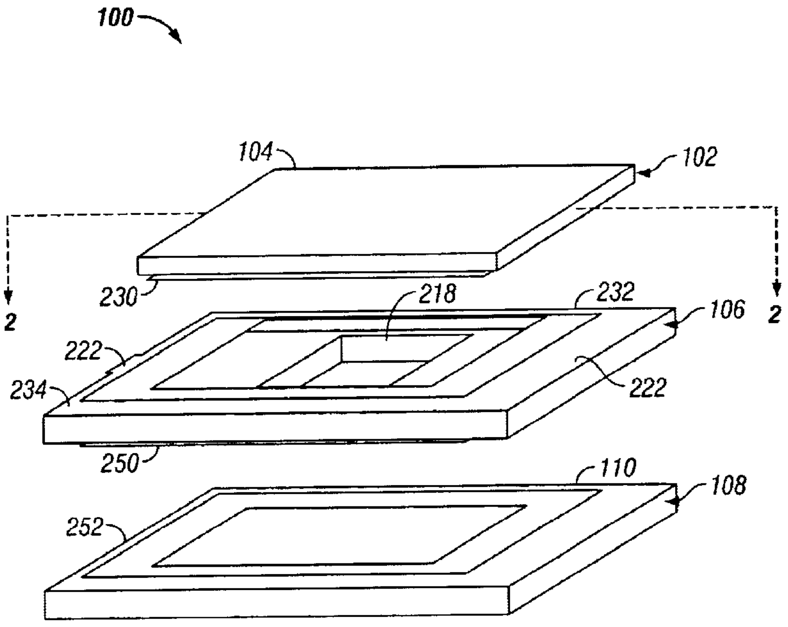
(57) **ABSTRACT**

A micro electromechanical system (MEMS) broad band incandescent light source includes three layers: a top transmission window layer; a middle filament mount layer; and a bottom reflector layer. A tungsten filament with a spiral geometry is positioned over a hole in the middle layer. A portion of the broad band light from the heated filament is reflective off the bottom layer. Light from the filament and the reflected light of the filament are transmitted through the transmission window. The light source may operate at temperatures of 2500 K or above. The light source may be incorporated into an on board calibrator (OBC) for a spectrometer.

6 Claims, 6 Drawing Sheets



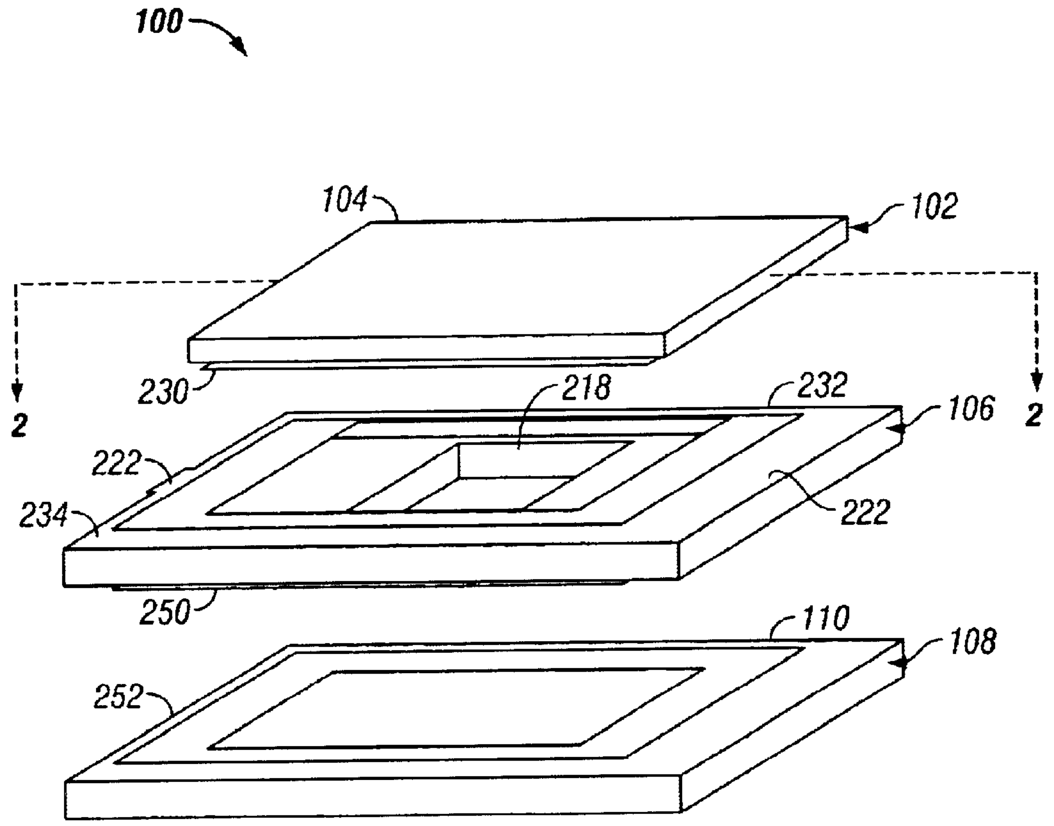


FIG. 1

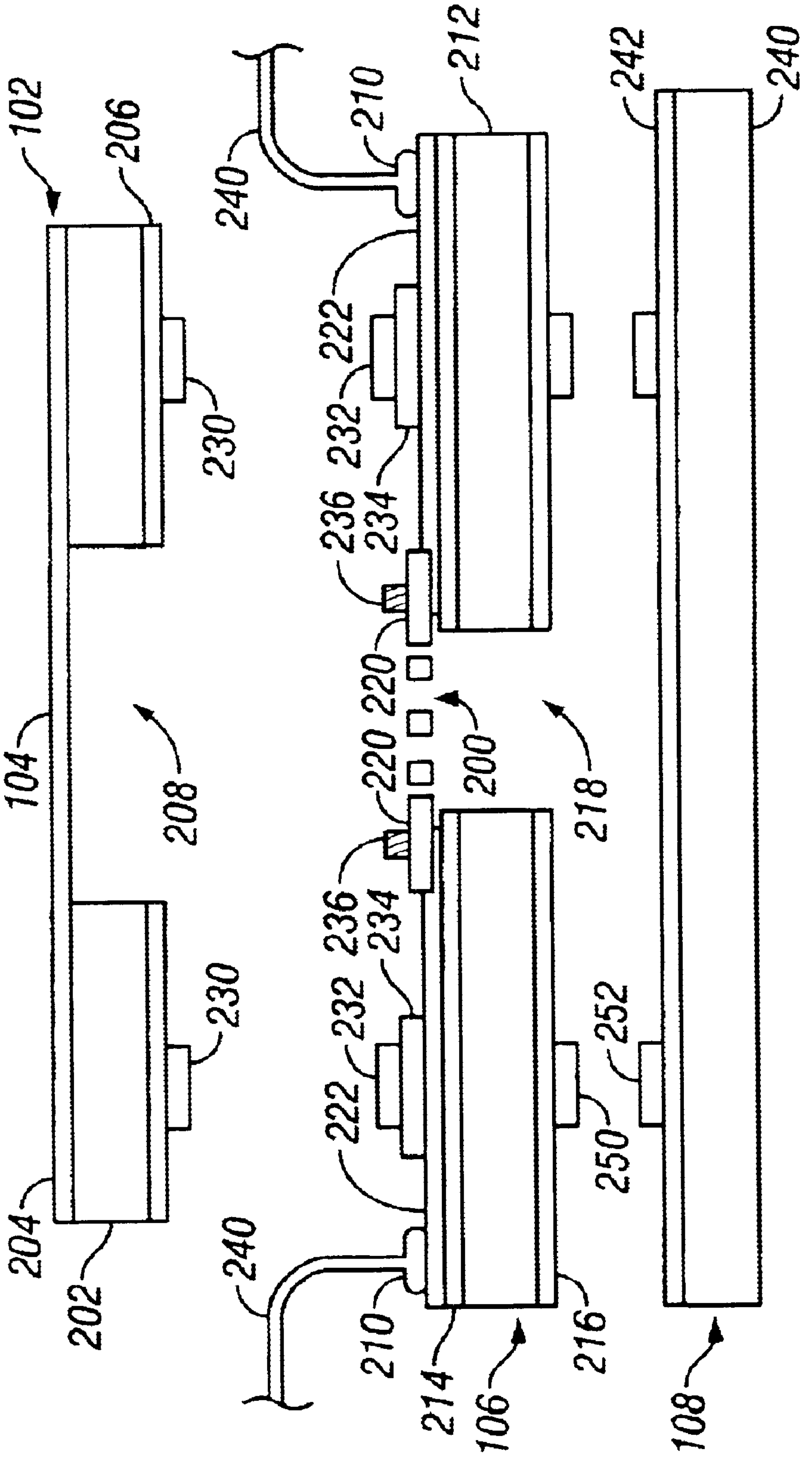

102
206
104
208
230
230
204
202
240
210
212
222
232
234
236
220
220
220
200
218
236
234
232
222
240
210
214
106
216
242
240
252
250
108

FIG. 2

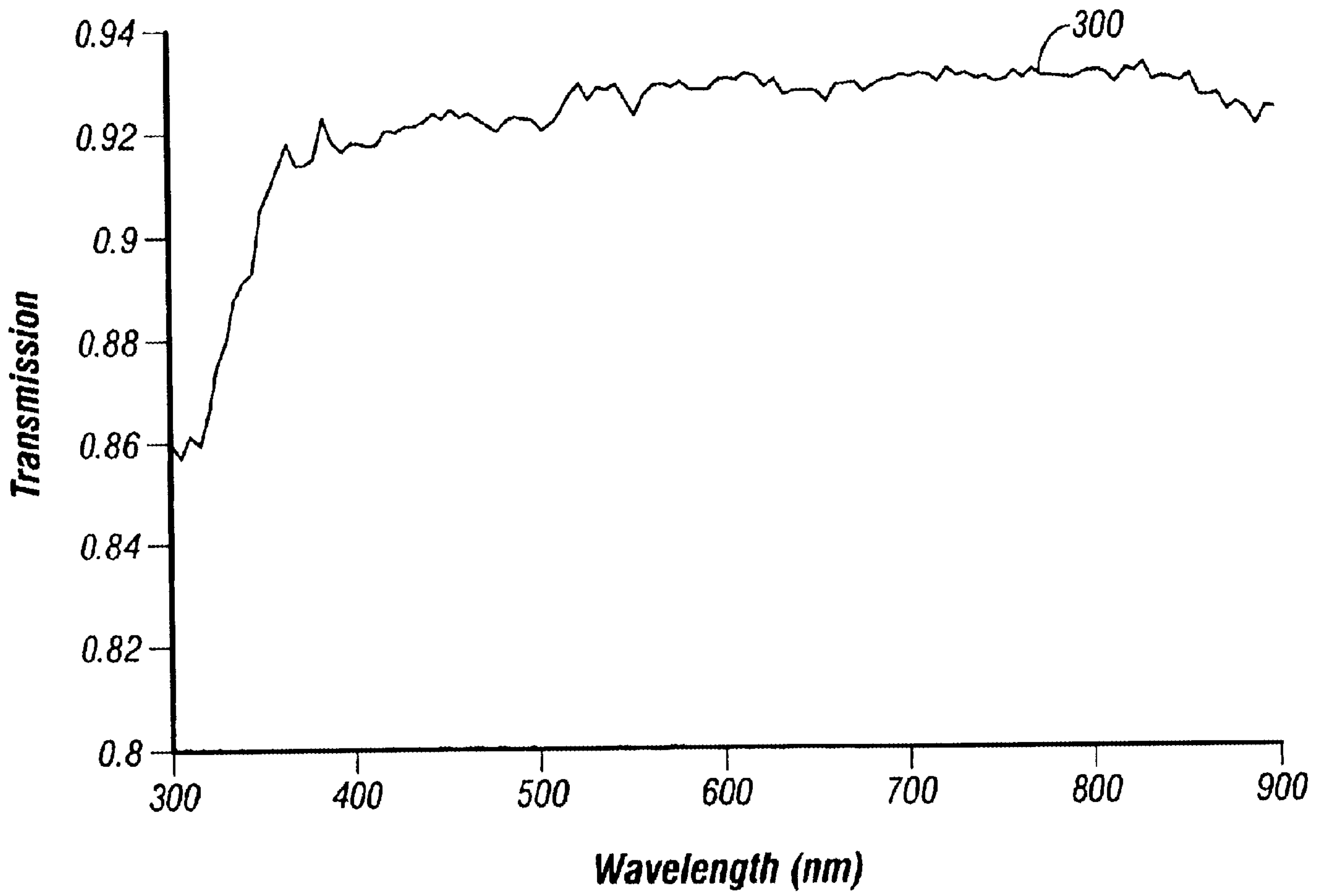

300
0.94
0.92
0.9
0.88
0.86
0.84
0.82
0.8
Transmission
300
400
500
600
700
800
900
Wavelength (nm)

FIG. 3

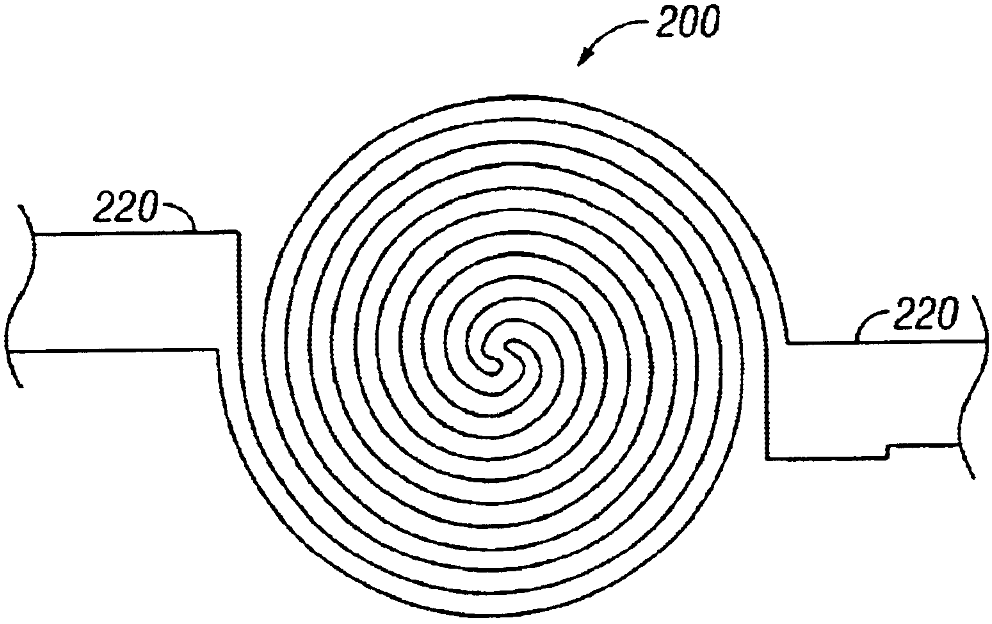


FIG. 4

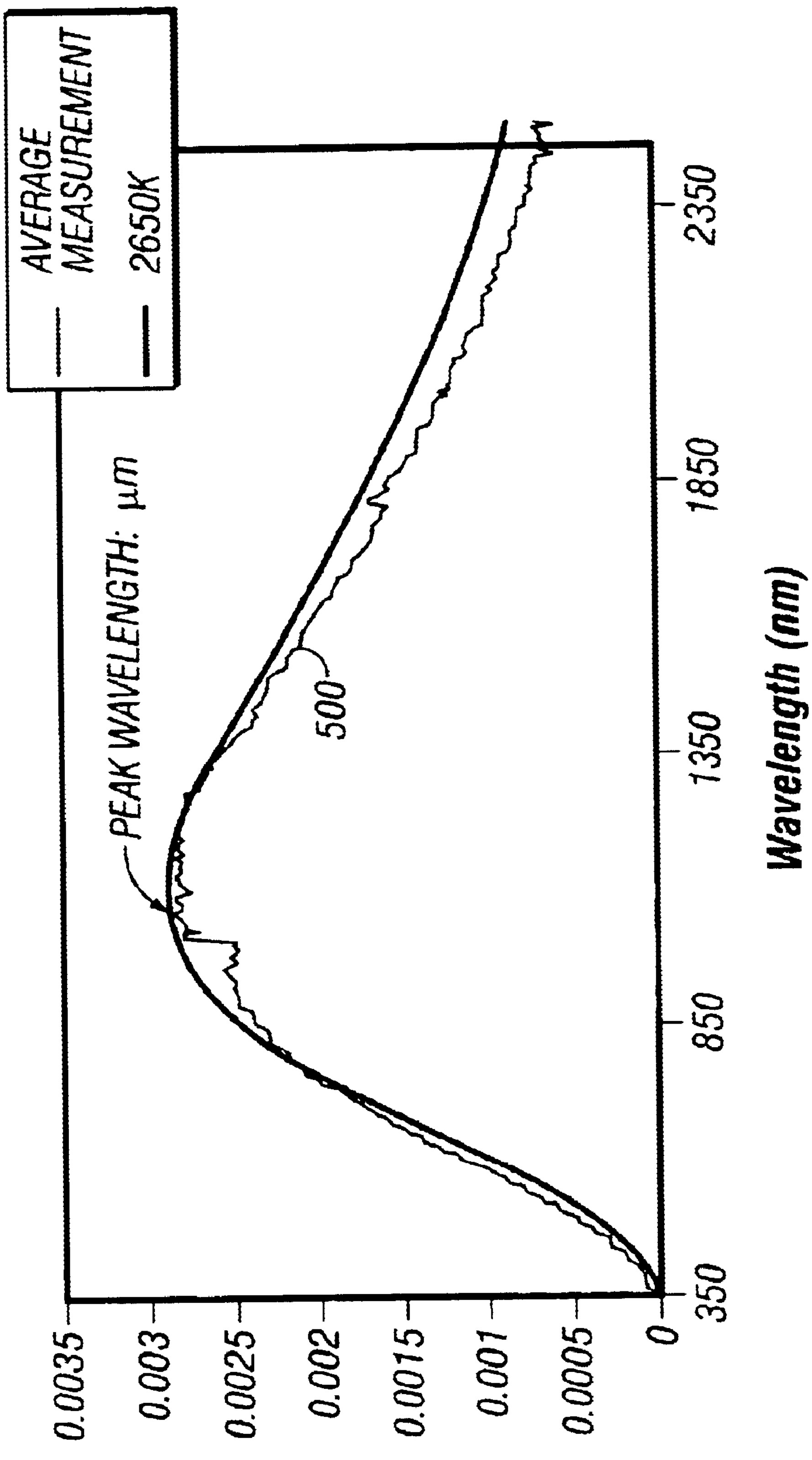

AVERAGE MEASUREMENT
2650K
PEAK WAVELENGTH: µm
500
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
350
850
1350
1850
2350
Wavelength (nm)

FIG. 5

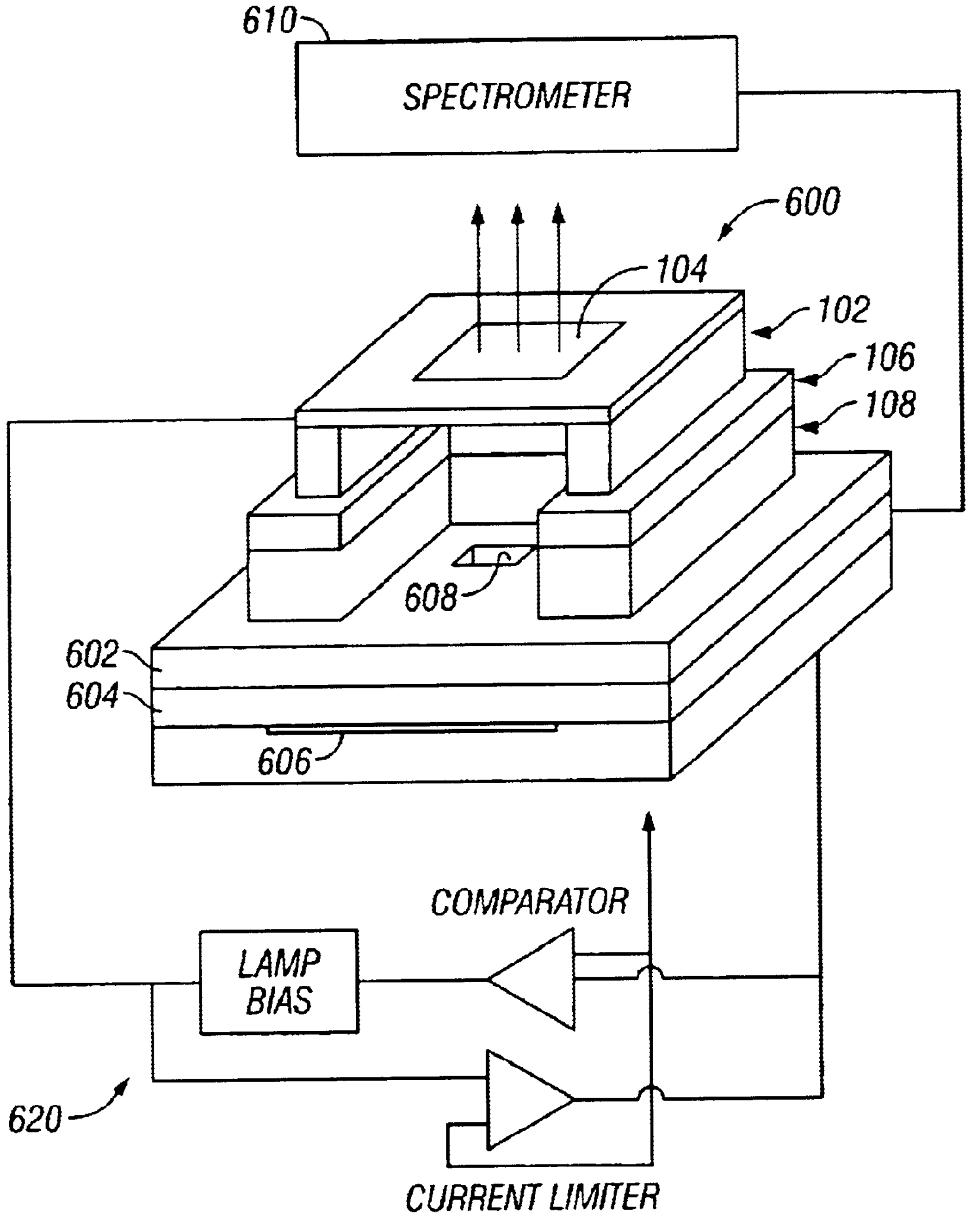

610
SPECTROMETER
600
104
102
106
108
608
602
604
606
COMPARATOR
LAMP BIAS
620
CURRENT LIMITER

FIG. 6

SILICON MICROMACHINED BROAD BAND LIGHT SOURCE

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a divisional of U.S. application Ser. No. 09/613,818, filed Jul. 10, 2000, (abandoned) which claims priority to U.S. provisional applications serial No. 60/142,989, filed Jul. 8, 1999, and serial No. 60/190,702, filed Mar. 17, 2000.

ORIGIN OF INVENTION

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (35 U.S.C. 202) in which the Contractor has elected to retain title.

BACKGROUND

On board calibrators (OBCs) are used to improve the performance of spectrometers used for terrestrial observation as well as planetary exploration missions. OBCs enable acquisition of quantitative and accurate spectral data. Although such OBCs are desirable components, they may be used only when the missions are large enough to accommodate the relatively large size, mass and power requirements of conventional OBCs.

OBCs utilize a stabilized broad band light source. Broad band light sources fabricated from off-the-shelf light bulb technology and discrete electronics are relatively large, have high power requirements and long start-up stabilizing times, and give off a considerable amount of heat.

Accordingly, it is desirable to provide a low mass, low power, monolithic broad band light source in a rugged package that may be integrated with electronics and optical fibers for use in an OBC.

SUMMARY

An incandescent light source according to an embodiment includes a top layer having a transmission window attached to a filament mount including a cavity. A spiral filament is connected to the filament mount and extends across the cavity. The filament is positioned under the transmission window.

The filament may be tungsten and operate at a temperature of at least about 2500 K. The filament may be at least 10 μm thick, with a fill factor between about 33% and 90%.

A bottom reflector layer may be attached to the other side of the filament mount with a reflective metal layer facing the filament.

The transmission window may be transparent to wavelengths between about 500 nm and 900 nm. The transmission window may include, for example, silicon nitride or pyrex.

The light source may operate at an input power of less than or equal to about 2 W.

The light source may be integrated into an on board calibrator (OBC) to be used in a spectrometer.

The top layer may be fabricated by depositing a 1000 Å layer of silicon nitride on either side of a silicon substrate and forming a transmission window by etching a cavity through the bottom silicon nitride layer and bulk silicon. According to an alternate embodiment, the transmission window may be a pyrex plate.

The middle layer may be fabricated by depositing a 1000 Å layer of silicon nitride on both sides of a silicon substrate and etching a hole through the middle layer. Leads may be deposited on either side of the hole and the filament ends attached to the leads, such that the filament extends across the hole. The leads may extend beyond the end of the top layer where wire bonded leads provide electrical connection to the device.

The bottom layer may be formed by depositing a reflective metal film on a silicon substrate. The three layers may be stacked and oriented such that the transmission window is positioned over the filament and the reflective metal film faces the filament. The three layers may then be bonded together.

The details of one or more embodiments of the invention are set forth in the accompanying drawings and the description below. Other features, objects, and advantages of the invention will be apparent from the description and drawings, and from the claims.

DESCRIPTION OF DRAWINGS

FIG. **1** is an exploded perspective view of an incandescent light source according to an embodiment.

FIG. **2** is an exploded cross-sectional view of the embodiment of FIG. **1** taken along line **2**—**2**.

FIG. **3** is a graph showing transmission through a pyrex transmission window in a light source according to an embodiment.

FIG. **4** is a plan view of a spiral filament according to an embodiment.

FIG. **5** is a graph showing optical output of the light source of FIGS. **1** and **2** over a broad spectrum of wavelengths.

FIG. **6** is a schematic diagram of an on board calibrator (OBC) according to an embodiment.

DETAILED DESCRIPTION

FIGS. **1** and **2** show exploded views of a micro electromechanical system (MEMS) broad band incandescent light source **100** according to an embodiment. The light source includes three bonded silicon layers. These layers include a top layer **102** having a transmission window **104**, a middle filament mount layer **106**, and a bottom layer **108** having a reflector **110**. The entire structure may be about 8 mm thick.

The top layer **102** includes the transmission window **104** to transmit the light produced by a filament **200** (FIG. **2**). The top layer **102** includes a silicon substrate **202** with top and bottom silicon nitride layers **204**, **206**. A cavity **208** is formed through the center of the substrate **202** and bottom silicon nitride layer **206**. The free standing portion of the top silicon nitride layer **204** serves as the transmission window **104**. The transmission window is transparent to a broad spectrum of light, including wavelengths between about 500 nm to 900 nm.

According to an alternate embodiment, the transmission window **104** may be a pyrex cover slip that is bonded anodically to the silicon substrate, with no intervening silicon nitride layer. The pyrex transmission window is also transparent to light having wavelengths between about 500 nm to 900 nm. FIG. **3** illustrates a transmission response curve **300** for the pyrex coverslip according to an embodiment. The pyrex cover slip may be thicker and more mechanically robust than the nitride layer, but may require more fabrication steps and may add to the thickness of the transmission window and the overall final device.

Different materials may be used for the transmission window to transmit other portions of the wavelength spectrum, for example, the infrared (IR) portion. By changing the material of the transmission window, the output optical spectrum may be tailored to a particular need.

The middle layer **106** provides a mount for the tungsten filament, a wire bond pad **210** with a wire bond lead **240** for wire bonding to external packaging, and electrical leads **222** between the filament **200** and wire bond pads **210**. The middle layer **106** includes a silicon substrate **212** with top and bottom silicon nitride layers. A hole **218** is formed through the silicon substrate and top and bottom nitride layers **214, 216**. The tungsten filament **200** may have a spiral geometry, such as that shown in FIG. **4**, and extends across the hole **218**. The filament ends **220** are connected to wire bond pads **210** on either side of the hole by two electrical leads **236**. The electrical leads **222** may Ti/Pt/Au islands which are used to electrically connect the filament to an external power supply.

A filament with a thickness of about 10 μm or greater may avoid significant losses due to evaporation, hence improving the lifetime of the filament. According to an embodiment, the spiral tungsten filament **200** may be about 25 μm thick, with each spiral having an area of about 1400 μm×1400 μm. The spiral filament shown in FIG. **4** has a fill factor of about 50%, where the fill factor is the ratio of surface area of material to the total area. The filament fill factor may be in a range of about 33% to about 90%. At a fill factor of 90%, the distance between adjacent tungsten coils is about 5 μm. The higher the fill factor, the more densely packed the filament, which may produce a more intense and uniformly distributed light source. The limiting factors for the fill factor include electrical shorting and arcing between the spirals.

The top layer **102** and middle layer **106** may be connected by corresponding Ti/Pt/Au bonding rings **230, 232**. A 1 μm layer of nitride **234** may be provided to insulate the wire bond leads on the middle layer **106** from the bonding ring **232**.

The bottom reflector layer **108** provides a reflective surface to improve transmission through the transmission window **104** above. The bottom reflector layer includes a silicon substrate **204** with a reflective metal layer **242**. The reflective layer **242** may be a Ti/Pt 200/1000 Å reflective film. Silver may also be used as a reflective material. The bottom layer **108** may be bonded to the middle layer **106** by corresponding Ti/Pt/Au bonding rings **250, 252**. The thermal compression of these pairs of Ti/Pt/Au rinds (**230** and **232**) and (**250** and **252**) may be held at a pressure of about 10^{-6} Torr or in an inert atmosphere at or slightly below atmospheric pressure to provide a hermetic seal.

According to an embodiment, the MEMS broad band incandescent light source **100** may be produced by fabricating the three layers and bonding them together. The top layer **106** may be fabricated by depositing a 1000 Å low stress nitride film **204, 206** onto the top and bottom surfaces of a 400 μm thick bare silicon wafer using a plasma enhanced chemical vapor deposition (PECVD) process. A Ti/Pt/Au 200/200/2000 Å bonding ring **230** may then be evaporated onto the unpolished side of the silicon wafer using a liftoff process. The bottom nitride layer **206** and the bulk silicon may be etched to reveal the top nitride window **104**. The etched cavity **208** is wider than the filament length to allow the 25 μm thick filament **200** mounted to middle layer **106** to fit inside the cavity **208**.

The middle layer **106** may be fabricated by depositing a 1000 Å PECVD silicon nitride layer **214, 216** on the top and bottom surfaces of a bare silicon wafer. The two Ti/Pt/Au electrical leads **222** may be evaporated in the radial direction to electrically connect the filament **200** with the wire bond pads **210** where the filament is a spiral with filament ends **220** as shown in FIG. **4**. A 1 μm layer of PECVD silicon nitride **234** may be deposited on the electrical leads **222** for electrical insulation. The insulating nitride layer may be patterned in a ring and etched in a fluorine reactive ion etcher (RIE). A Ti/Pt/Au 200/200/2000 Å bonding ring **232** may be evaporated onto the nitride insulation ring using a liftoff process. The bonding ring **232** matches the bonding ring **230** on the top layer **102**. A Ti/Pt/Au 200/200/2000 Å bonding ring **250** may then be deposited on the unpolished side of the wafer using a liftoff process. This bonding ring **250** functions as a bonding ring that will attach to the bonding ring **252** on the bottom reflector layer **108**. Deep reactive ion etching (DRIE) may be used to etch the hole through the entire silicon wafer.

The bottom reflector layer may be fabricated by evaporating a Ti/Pt 200/1000 Å reflective film **242** onto a bare silicon wafer. As described above, silver may also be used as a reflective material. A Ti/Pt/Au 200/200/2000 Å ring **252** may then be evaporated onto the reflective layer for thermal compression bonding to the middle layer **106**.

The tungsten filament **200** may be fabricated from a 25 μm thick tungsten sheet. A photoresist may be patterned with the filament geometry on both sides of the sheet, and the sheet chemically etched from both sides in a wet $K_3Fe(CN)_6$ etch to form a planar spiral filament. Etching from both sides may reduce lateral etching from 25 μm to 12.5 μm and thereby improve the final device fill factor. According to alternate embodiments, other methods such as laser etching may be employed to further improve filament fill factor.

The top, middle, and bottom layers may then be individually diced. The filament ends **220** may be attached to the electrical leads **222** on the middle substrate over the hole by two gold ribbons. The three layers are then oriented to align the bonding rings (**230, 232, 250, 252**), and the entire stack bonded under reduced pressure (10^{-6} Torr) or in an inert atmosphere at or near atmospheric pressure in a thermal compression bonder. Eutectic bonding may also be employed for bonding the three layers.

To avoid damaging the nitride transmission window **104**, it may be desirable to place a flat pyrex piece of device size above the nitride transmission window **104**, and a graphite piece above the pyrex piece to protect the device against the surface roughness of the compression bonder piston.

The expected output optical power of the light source **100** may be calculated from the filament area, as shown in Equation (1).

$$\text{Area}=\Pi * r^2 \tag{1}$$

Since there are two sides to the filament **200**, there is a multiplication factor of two, but because the fill factor of the present embodiment is ½, the two terms cancel. Accordingly, the radiant power should be the product of the total radiation intensity for tungsten, which is about 110 Watts/square cm at 2800 K, and the filament area, as given in Equation (2). For a spiral filament with a radius of 0.07 cm, the area would be 0.15 cm^2, yielding:

$$110\ (\text{Watts/cm}^2)*0.015\ (\text{cm}^2)=1.69\ \text{W}. \tag{2}$$

For an operating temperature of 2500 K, the total radiation intensity drops the value from 110 to 66.1. Hence, the filament should radiate 0.992 W. For a fill factor of ¼ instead of ½, the radiant power would drop to 0.496 W.

A MEMS broad band incandescent light source **100** according to the embodiment shown in FIGS. **1** and **2** was tested. Optical output data of the light source was taken through a vacuum chamber window. Measurements were taken using an Analytical Spectral Devices (ASD) Fields Spectrometer, which can measure wavelengths of about 350 nm to 2500 nm. The spectrometer was used in conjunction with a standard 1000 W lamp and a spectralon panel that is approximately 99% reflective. A thirty-eight fiber cable (some fibers provided for visible wavelengths and some for IR) was used to transfer the light from the light source to the spectrometer with an 8-degree field-of-view. FIG. **5** shows an optical output response curve **500** of the light source. Discontinuities in the graph shown in FIG. **5** may be attributed to the changing of detectors. A blackbody approximation was fit to the experimental data, which gave a blackbody temperature of 2650 K. The light source was driven at 170 mA at 7.356 V, providing an input power of 1.25 W.

According to an embodiment, the MEMS structure may be hermetically sealed to prevent oxidation of the filament, as such oxidation may reduce the lifetime of the light source. The light source **100** may be sealed in sealing chamber which may be depressurized to form a vacuum, or filled with a chamber gas. The chamber gas may include, for example, nitrogen or halogen-doped nitrogen. A halogen-doped nitrogen environment may reduce evaporative losses by setting in motion a chemical reaction cycle that removes evaporated tungsten off of the transmission window and redeposits it on the filament **200**.

According to an embodiment, the output of the device may be coupled to an optical fiber. A lens structure may be fabricated into the transmission window for coupling to an optical fiber. The lens structure may be, for example, a ball lens or a graded-index (GRIN) lens.

When a tungsten filament is heated for the first time, there is a tendency for it to distort slightly due to grain growth and forces from thermal expansion. This may cause part of the planar filament to move in or out of plane. If the filament is coupled to the fiber by the normal two-ball lens system, a small change in the position of the source may be imaged as a small change in the image position. Because the image of the filament is considerably larger than the core of the fiber, this movement may have little effect on the amount of light entering the fiber. If the structure is set before the optics are assembled, any distortion in the filament may be corrected by the placement of the optics.

The MEMS broad band incandescent light source **600** may be incorporated into an on board calibrator (OBC). As shown in FIG. **6**, the MEMS light source **600** has a similar structure to that shown in FIGS. **1** and **2**. The light source is attached to a ceramic substrate **602**, a bandpass filter **604**, and a photodetector **606**. A transmission window **608** is provided in the bottom reflector layer **108** to pass light rays from the filament **200** through the ceramic substrate **602** and band pass filter **604** to the photodetector **606**. The MEMS OBC may include a feedback loop **620** that maintains the brightness of the light source at a substantially constant level.

The MEMS OBC **600** shown in FIG. **6** may have a volume of about 30 cm^3, mass of about 50 g, and consume about 2 W in operation. Such a MEMS OBS is advantageously smaller in size and has a smaller mass and power consumption than OBCs employing off-the-shelf light bulb technology and discrete electronics.

A MEMS broad band incandescent light source according to an embodiment may be incorporated into various sensor devices such as a spectrometer **610**. For example, the light source may be incorporated into an optic temperature sensor system to detect exhaust gas temperature (EGT) of an airplane during flight.

A number of embodiments of the invention have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the invention. Accordingly, other embodiments are within the scope of the following claims.

What is claimed is:

1. A method comprising:

depositing a layer of silicon nitride on each of two faces of a first silicon substrate;

etching a cavity through the first silicon substrate and one of the silicon nitride layers to form a transmission window comprising silicon nitride;

forming a hole in a second silicon substrate;

depositing leads on either side of the hole;

positioning a filament comprising tungsten and having a spiral geometry across said hole;

connecting each of two ends of the filament to an associated one of the leads;

depositing a reflective film on one face of a third silicon substrate;

stacking the first, second, and third silicon substrates, in that order, and orienting said substrates such that the transmission window is positioned over the filament and the reflective film faces the filament; and

bonding the first, second, and third silicon substrates together.

2. The method of claim **1**, further comprising:

depositing a bonding ring on a face of the first silicon substrate opposite the transmission window;

depositing a bonding ring on each of two faces of the second silicon substrate; and

depositing a bonding ring on the reflective film of the third silicon substrate.

3. The method of claim **2**, further comprising providing an insulating layer between the leads on the second silicon substrate and the bonding ring on that face of said second substrate.

4. The method of claim **1**, wherein the silicon nitride layers on the first silicon substrate are about 1000 Å thick.

5. The method of claim **1**, further comprising depositing a 1000 Å layer of silicon nitride on each of two faces of the second silicon substrate.

6. The method of claim **1**, wherein the filament has a thickness of at least about 10 μm.

* * * * *