HOT SELF BOLOMETER PHOTONIC CRYSTAL BASED HYDROCARBON SENSOR

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ABSTRACT

We report a novel combination infrared source and bolometer that uses a photonic crystal to emit narrow band infrared energy that is used to measure hydrocarbon gasses. The device emits infrared radiation aided by a photonic crystal at the hydrocarbon wavelength of $3.3\text{ }\mu\text{m}$ and suppresses emission at other wavelengths. The amount of radiation that returns to the device after emission, reflection off a mirror, and passing through a gas sample is related to the partial pressure of methane or other hydrocarbons in the sample being measured. The device can detect gas concentrations down to 500 ppm of methane and has a sensitivity of up to $4\text{ }\mu\text{V/ppm}$.

INTRODUCTION

We present a novel photonic crystal based combination infrared source and bolometer that is used to detect hydrocarbon gasses. The highly integrated single component infrared device contains all the elements of a non dispersive infrared optical bench in a single MEMS chip, unlike most infrared based gas sensors which separate the infrared source and detector. The device emits infrared radiation via a photonic crystal with a tuned output of 90% of the theoretical maximum at the hydrocarbon wavelength of $3.3\text{ }\mu\text{m}$ and suppresses emission at other bands. The amount of infrared radiation that returns to the device after bouncing off a retro-reflecting mirror depends on the concentration of methane present between the device and the mirror. This paper will present the operation, fabrication, wafer level packaging, testing, and performance of the device. This is the first time that this device has been reported in the trade or technical literature and the first time that this type of device has been reported to the MEMS community [1].

OPERATION

The device uses two thermally isolated filaments, $1.5\text{ mm} \times 3\text{ mm}$ in size that are resistively heated to 300°C . A photonic crystal, incorporated into the thermally isolated bulk-micromachined filaments, facilitates emission of infrared radiation, at the methane absorption wavelength of $3.3\text{ }\mu\text{m}$ and suppresses blackbody emission at wavelengths outside this band yielding high power efficiency and gas specificity. Without the photonic crystal, the peak of the emitted blackbody radiation would be near $5.2\text{ }\mu\text{m}$ in accordance with Wein's law. Because of the photonic crystal's geometry, the infrared emission is non-Lambertian and is emitted preferentially in a direction normal to the surface of the filament. The infrared radiation passes through a silicon cap wafer and out of the vacuum sealed package and then through the gas being analyzed. The infrared radiation reflects off a mirror and back through the gas being analyzed, through the silicon cap and onto the filament. In our test setup, the optical path length is about 5 cm. The photonic crystal has a high emissivity at $3.3\text{ }\mu\text{m}$ (approximately 90%), and does not transmit infrared radiation so almost all of the infrared radiation that is incident on the photonic crystal is absorbed. Because of the high thermal resistance of the filament (150 K/W), the incident infrared energy causes the temperature of the filament to increase. The filament has a temperature coefficient of resistance of 0.4%, and thus operates as a bolometer, making the resistance change of the sensor dependent on the partial pressure of the gas species being analyzed. To compensate for changes in the ambient temperature and the supply

voltage and to allow incorporation of the device into a Wheatstone bridge circuit, one of the two filaments is blinded with a gold film on the cap wafer. The device also has an on-chip thermistor to facilitate second order temperature corrections. The vacuum encapsulation and very high power conversion efficiency combine to keep the case temperature just above the ambient temperature, thus enabling intrinsically safe operation in potentially explosive environments. Any breach in the wafer level package that would expose the hot filaments to flammable gasses would immediately cause the device to lose thermal isolation and cool the filament. Figure 1 pictorially demonstrates how the device operates as a gas sensor.

Figure 1 Pictorial depiction of device operation that shows infrared energy generation, absorption of the infrared by gasses, reflection off the mirror and return to the device. A change in the amount of infrared energy absorbed by the device is proportional to a temperature change and a resistance change in the filament, which is proportional to a change in the concentration of the gas being measured.

PHOTONIC CRYSTAL THEORY

The photonic crystal is used in this device to increase the efficiency and decrease the cross sensitivity of the device by reducing the out of band emission of infrared light. Narrow emission is important to reducing cross sensitivity because some common atmospheric gasses absorb infrared radiation near the methane $3.3\text{ }\mu\text{m}$ line including water vapor at $2.7\text{ }\mu\text{m}$ and CO_2 at $4.2\text{ }\mu\text{m}$. Therefore, tailoring the emission of infrared energy so there is no radiation at these bands is critical to eliminating cross sensitivity. If the radiation emitted by the device was absorbed by a gas species other than the species of interest, the sensor would indicate a higher gas concentration than what was actually present. A device that emits a narrow band of infrared eliminates this cross sensitivity. Also, by reducing the bandwidth of the emitted infrared light, the energy loss due to radiation is reduced and less energy is needed to heat the device.

We fabricate the photonic crystals from a silicon substrate, a thin insulating oxide layer, and a conductive metal filament layer on top. The entire structure is pierced with an array of micrometer sized holes that have a periodic spacing. In the same way that the

periodic arrangements of atoms in a solid state device changes the allowed and forbidden energy bands and energy bandgaps for electrons from the energy levels available in individual atoms, the periodic arrangement of recesses form alternating regions of low pressure gas and silicon or a two dimensional photonic crystal, which causes the establishment of photonic bandgaps. Photonic bandgaps are analogous to electron bandgaps, they are regions where certain wavelengths are not allowed. Our periodic structure creates a sharp photon absorption profiles aided by surface plasmons, which are longitudinal modes of electromagnetic radiation propagating along the surface that exponentially decay away from the interface. Photonic crystals are usually designed using finite element codes. Faraday's law and Ampere's law are expressed in terms of the magnetic field, $\mathbf{H}$, and the Maxwell eigen-value problem is solved. Equation 1 shows the solution of Faraday's and Ampere's law in terms of the magnetic field where ϵ is the dielectric constant and ω equals 2π times the frequency.

$$\nabla \times \frac{1}{\epsilon} \nabla \times \mathbf{H} = \left(\frac{\omega}{c} \right)^2 \mathbf{H} \quad (1)$$

A good summary of our photonic crystal structure can be found in references [2-4]. A SEM image of the photonic crystal is shown in figure 2.

Figure 2 Photograph of the dry etched photonic crystal.

FABRICATION

To improve efficiency, the filaments are thermally isolated from the substrate with a bulk micromachining etch and vacuum encapsulation. All the fabrication is done by Innovative Micro Technology of Santa Barbara, California [5]. The three wafer stack is bonded together using a glass frit bonding process. The top wafer in the stack is high resistivity silicon that is transparent in the infrared and allows optical energy to enter and leave the device. The proprietary vacuum bonding process has a stabilized base pressure of less than 20 mT. Figure 3 is a photograph of the devices after dicing.

Figure 3 Devices after dicing. The photograph illustrates the 3 wafer stack and the blinding of one filament to form a reference. The device is constructed from a three wafer stack. The wire bond connections are made to the exposed ledge on the middle wafer.

Figure 4 shows the relationship between the pressure inside the devices and the high current resistance (10 mA) divided by the low current resistance (100 μ A). The ratio is close to 1.0 at atmospheric pressure. Figure 4 implies the increased sensitivity that is created by vacuum sealing the device. At low pressures, the thermal resistance of the filament is dominated by the structural silicon support arms. At high pressures, the thermal resistance is dominated by the thermal conductivity of the gasses surrounding the sensor and is not dependent on the pressure because the mean free path of the gas molecules is much smaller than the distance from the filament to the cap wafer. Thermal isolation is one characteristic measured during testing that separates acceptable device from rejected devices.

Figure 4 The R_{hot}/R_{cold} resistance ratio as a function of pressure. R_{hot} is measured at 10 mA and R_{cold} is measured at 100 μ A. At very high and very low pressures, this ratio and the thermal isolation is independent of pressure. If the experiment had been continued to 0.001 or 0.0001 T the hot resistance to cold resistance would not have exceeded 1.75.

One interesting discovery was that the amount of surface area of the photonic crystal and the diameter of the holes influenced the final base pressure that was reached during packaging. During the prototyping of the device, we varied the size of the photonic crystal holes and changed the spacing. The pressure inside the wafer level package increased as the diameter of the photonic crystal holes decreased because of the decreased pumping conductance. Conductance is dependent on the cube of the diameter when molecular flow is the dominate flow mechanism. We also changed the density of the holes in the photonic crystal and discovered that devices with a higher density of holes, and more surface area, had a higher base pressure than units with a lower hole density. This correlates with theory because the main cause of residual gasses inside the devices after sealing is outgassing from surfaces. In this device, about 50% of the total surface area inside the devices is from the sides of the holes. The results of this experiment are shown in figures 5 and 6.

Figure 5 Pressure histogram showing the relationship between photonic crystal hole diameter and the thermal isolation (ratio of 10 mA resistance to 100 μ A resistance). The diameters are expressed as in terms of the smallest hole diameter or 1.1 or 1.2 times the smallest hole diameter. A value of 1.7 corresponds to a pressure of 9mT and a value of 1.4 corresponds to a pressure of 60 mT. Hole density was held constant in this experiment.

Figure 6 Pressure histogram showing the relationship between the number of holes in the filament and the thermal isolation (ratio of 10 mA resistance to 100 μ A resistance). The holes account for about 50% of the surface area that is sealed inside the device.

FINAL ASSEMBLY AND TESTING

To reduce costs and monitor yield, the devices are tested on a wafer level before dicing. The defects that are found during this step are thermal isolation problems and electrical resistance problems. Thermal isolation is determined by using the device as a pirani gauge and measuring the ratio of the resistance at a high current level (10 mA) and a low current level (100 μ A). If the device is thermally isolated, the resistance changes by more than 50% from the low to the high current level. Devices that are not vacuum sealed, in contrast, exhibit a less than 10% change in resistance between the high and low current levels. Figure 2 shows a graph of the ratio of hot resistance to the cold resistance as function of pressure.

After testing on a probe station at Innovative Micro Technologies, the devices are shipped to Solid State Testing of Billerica, MA where they are die attached into 28 pin leadless chip carriers LCCs and wire bonded using thermosonic gold ball bonding [6]. Then they are shipped to ICx Photonics where they undergo gas testing. The electrical circuit is a Wheatstone bridge followed by amplification. The ICx Photonics automatic gas testing station, shown in figure 7, can expose several sensors in parallel to a predetermined series of gas concentrations. The gas sensitivity is influenced by defects in the transparent cap wafer. Issues in packaging and those due to electrical noise are also discovered and eliminated during gas testing.

Using results similar to figures 8 and 9 the performance of the device was analyzed. For an optical path length of 5.2 cm and a bridge voltage of 5 V, the device has a noise equivalent methane level in the 500 ppm range, a sensitivity of 3 to 4 μ V/ ppm, and a response time of 1 s.

Figure 7 Automatic testing setup. The test gas flows through the tubes to the twelve gas testing locations. The domes are the mirrors and the sensors sit beneath them along with the amplification circuitry.

Figure 8 Time response of the gas sensor to 25000 ppm of methane alternating with nitrogen.

Figure 9 Output voltage as a function of gas concentration for a series of devices. . These devices were tested at half the gain setting of the device in figure 8. The minimum concentration in this graph is 1000 ppm.

APPLICATIONS

The 70 mW that this device consumes makes it ideal for low power portable safety applications such as detecting explosive gasses in coal mines. The sensor and supporting circuitry are intrinsically safe because the voltages, capacitance and surface temperatures provide certifiable protection ignition in a potentially explosive atmosphere. The low power levels also make it

compatible with battery powered portable operation and remote monitoring applications. Because of the tailored infrared emission, the device has a low response to humidity, CO₂, and other gasses that are found in coal mines. Because the gas does not contact the sensing element, it is not susceptible to poisoning and hysteresis that plague electrochemical sensors. The device is compatible with the ICx Photonics 4P sensor readout module [7].

CONCLUSION

This paper reports a novel combination infrared source and bolometer that uses a photonic crystal to emit and detect precisely tailored infrared energy that is used to detect hydrocarbon gasses. The highly integrated single component infrared device contains all the elements of a non dispersive infrared optical bench in a single MEMS chip, unlike most infrared based gas sensors which separate the infrared source and detector. The device emits infrared radiation with a photonic crystal with a tuned output of 90% of the theoretical maximum at the hydrocarbon wavelength of 3.3 μ m and suppresses emission at other bands. The amount of radiation that returns to the device after emission, reflection off a mirror, and passing through a gas sample is related to the partial pressure of methane or other hydrocarbons in the sample being measured. The device can detect gas concentrations down to 500 ppm of methane and has a sensitivity of up to 4 μ V/ppm.

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