Fabrication and evaluation of a thermal sensor formed on a thin photosensitive epoxy membrane with low thermal conductivity

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Abstract. This article presents the fabrication and development of a thin metal film bolometer IR detector connected in a Wheatstone bridge configuration. The bolometer is constructed on a 4 µm thin self-supported SU-8 2002 membrane. A polymer material such as SU-8 has low thermal conductivity and is applied using standard photolithographic processing steps. The polymer could increase detector sensitivity and lower the production cost. Thermal simulation results are presented, which verify SU-8 as a better choice of materials compared to common membrane materials such as Si and Silicon nitride. Measurements on the fabricated nickel resistance bolometer on SU-8 2002 membrane show a sensitivity of 9.3 V/W when radiated by an IR laser with a wavelength of 1.56 µm.

1. Introduction

Thermoelectric sensors such as bolometer and thermopiles are used in a wide range of application areas. These areas include remote temperature measurements and gas detection using the non-dispersive infrared (NDIR) technique [1][2].

A bolometer used for thermal radiation detection consists of a resistance thermometer connected to an absorbing element with heat capacity C. The absorbing element is connected to a heat sink held at constant temperature via a thermal conductance G. Incident radiation is converted to heat by the absorbing element and an increase in temperature produces a change in electrical resistance proportional to the amount of incoming radiation. The performance of the bolometer is improved by selecting materials with high temperature coefficient of resistance (TCR), low thermal conductivity and small 1/f-noise. As thermal conductance, thin membrane materials like Si [3] and Silicon nitride[4] has effectively been used in existing thermoelectric sensors. These materials have the advantage of being compatible with standard silicon processing techniques, including high temperature steps up to at least 700 ºC. One drawback with these materials is their relatively high thermal conductivity. This lowers the temperature increase generated by the incoming radiation, and therefore the detector sensitivity. Using a membrane material with lower thermal conductivity, such as polymers, could increase the sensitivity. A polymer material which has becoming widely used in various types of micromachining and microfluidic devices is SU-8 [5]. SU-8 is an epoxy type negative UV photoresist, which was originally developed by IBM. SU-8 is applied using only standard photolithographic processing steps, and this could mean lower productions cost.
In this work, we present the development and characterization of a metal film resistance bolometer with a self-supporting membrane. The self-supported membrane is realized using silicon bulk micromachining techniques and consists of a 4 µm thin SU-8 2002 layer, fabricated by MicroChem. A thermal conductivity as low as 0.3 W/mK has been reported [6]. This could be compared with Si and Silicon nitride, having a thermal conductivity of 150 W/mK [7] and 3.2 W/mK [8], respectively. In the following sections, results from thermal simulations made for different membrane materials are shown. Results from characterization of the fabricated nickel (Ni) film bolometer connected in a Wheatstone bridge configuration are also presented.

2. Simulation

As a start of this study, we wanted to investigate how suitable SU-8 would be as a thermally insulating membrane compared to common membrane materials. Using the simulation software FEMLAB, thermal simulations comparing SU-8 2002 with common membrane materials as Si₃N₄ and Si was therefore performed.

2.1. Simulated structure

By using a device with symmetrical geometry, it was sufficient to simulate half of the detector area. Simulations were performed in 2D using cylindrical coordinates. With cylindrical coordinates, 3D effects were included and the number of mesh points was reduced and the simulation speed increased. The simulated structure consisted of a thin membrane connected to a silicon bulk with a thickness of 525 µm (Fig. 1). The width of the membrane was set to 0.9 mm and the thickness was chosen to 4 µm for the SU-8 and 1 µm for the Si and Silicon nitride. In the centre of membrane a 700 µm wide and 1000 Å thick nickel layer was deposited to simulate the metal film resistances. In case of SU-8, the metal was encapsulated in-between two 2 µm SU-8 layers. The thermal conductivity of the nickel layer was scaled to match a surface coverage of 50%. A 10µm thick infrared absorbing layer with the same thermal properties as SU-8 was added on top of the membrane. Boundary conditions for all borders, except for the bottom could be described by equation (1) [9]:

$\mathbf{n} \cdot (k\Delta \mathbf{T}) = q_0 + h(T_0 - T) + C(T_0^4 - T^4)$

Where $q_0$ is the inward flux and the convection parameter is described by the 2nd term. In simulations the convection heat transfer coefficient, $h$ was set to 10 W/m²K. The 3rd term models radiation heat transfer with the surrounding environment. The constant $C$ is the product of the surface emissivity $\varepsilon$ and Stefan-Boltzmann’s constant $\sigma = 5.67 \cdot 10^{-8}$ W/m²K⁴.

2.2. Simulation Results

The temperature increase in the Ni resistance caused by an incoming heat flux was simulated for structure described above. An inward heat flux with a power of 2.6W/m² was directed to the absorbing layer and 100% absorption was assumed. In Fig. 2, the generated simulation result is shown. As can be seen, the measured temperature increase is more than 30% higher the SU-8 2002 membrane compared to Silicon nitride, even though is much thicker. Compared with the Si membrane the difference is more than 19 times. On the other hand, due to material properties such as specific heat capacitance and
thermal conductivity, thermal saturation appears faster for Si and Silicon nitride membranes. The thermal time constant for the 4 µm SU-8 membrane is about 450ms.

**Figure 2.** Simulated temperature increase for different membrane materials.

**Figure 3.** Thermal response as function of metal thickness.

Detectors such as thermopiles typically consist of a large number of serially interconnected thermocouples, where the cold junctions are placed on the silicon bulk and the hot on the membrane. A large number of metal conductors connecting the membrane with the heat sink thermally shunts the membrane and lower the sensitivity. Using thinner metal layers decreases the shunting effect, but this increases the serial resistances and therefore also the noise. For a bolometer, having only a few metal wires connecting the bulk and the membrane this effect is limited. In figure 3, a simulation where the metal thickness was varied is shown for various membranes. As a comparison a similar simulations for a Ti/Ni thermopile on a SU-8 membrane is also shown. The simulated thermopile structure had a membrane with an area of 1.8 mm², and thermocouple junctions placed around the membrane edge. A surface coverage of 50% was assumed for the metal layer. As can be seen, the thermopile structure is much more sensitive metal thickness compared to the SU-8 bolometer. For the Si and Silicon nitride bolometer, thermal conductivity of the membrane is higher which makes them less sensitive to the thickness of the metal resistances.

3. Bolometer Fabrication

The starting material in the fabrication process was a 525 µm thick double polished <100>-orientated n-type silicon wafer. Thermal oxidation was performed to form a 5800 Å SiO₂ layer, and a layer of SU-8 2002 was added on the front side of the wafer. Using a spin speed of 3000 rpm resulted in a 2 µm thin SU-8 layer according to specifications. The SU-8 layer was then further soft baked, exposed with UV light and hard baked. Nickel resistances in a Wheatstone bridge configuration was created by electron beam evaporating 1000Å thin nickel layer on top of the SU-8. Etch openings in the backside SiO₂ layer was patterned and etched. The nickel layer was patterned and aligned towards the backside SiO₂ etch openings. Nickel etch was carried out using concentrated phosphoric acid heated to 40˚C. A second layer of SU-8 was then applied on top of the resistance bridge. The top SU-8 layer encapsulated the resistances in SU-8. This gave them both mechanical and chemical protection, but also some protection against corrosion in the application, which enhances the long-term stability. Openings in the top SU-8 layer were formed where electrical connection to the bridge could be created. Finally a single sided silicon etch using tetramethylammonium hydroxide (TMAH) was performed through the wafer. TMAH etching resulted in a 4-µm thin self-supported SU-8 2002 membrane with an area of 1.8x1.8 mm and a Wheatstone resistance bridge with two infrared sensitive elements encapsulated, figure 4. In figure 5 the fabricated detector is shown.
4. Detector Characterization

The resistive value of the evaporated nickel resistances was determined to 11.8±0.08 kΩ for each of the four resistances by I-V measurements. A maximum voltage of ±0.2 V was used to limit self heating effects. Since SU-8 is almost transparent to wavelengths in the infrared region, a black matte paint was added to the membrane for increased infrared absorption. The absorber was applied manually, and optical parameters such as absorption coefficient and reflectance were not specified. As a radiation source, a 1.56µm fiber laser with a power of 4.5mW was used. A HP33120A function generator was used to bias the bridge with a square wave of 2.5 V@10 Hz and a 50 % duty cycle. The unbalance in the bridge due to resistance mismatch was adjusted with an external circuit. The radiation was directed towards the center of the membrane, and the output from the detector was read with a National Instruments 16-bit USB-9215 DAQ. The maximum input voltage was set to ±0.5 V, giving a voltage resolution of 16µV. The infrared response of the bolometer is shown in figure 6. Equation (2) defines the sensitivity and assuming complete absorption of the incoming radiation yields in a sensitivity of 9.3 V/W.

\[ S = \frac{U_{out}}{P_{rad}} \]  

(2)
To maximize the response of the detector, the absorbed radiation power should be conducted through the membrane and in to the bulk. Due to cooling effects from the surrounding air by means of radiation, conduction and convections mechanisms this is not the case. However, in a vacuum chamber, the effects of convection can be discarded and the sensitivity could be increased [10]. For the SU-8 bolometer, a sensitivity increase of more than four times has been measured at pressure 0.03 torr, figure 7.

5. Summary and Conclusions
Critical parameters for sensitivity of thin metal film resistance bolometer are the TCR of the metal resistance and the thermal conductance to the heat sink. Choosing a metal with high TCR and a membrane with low thermal conductivity increases the detector sensitivity. This work has shown that epoxy based photoresist SU-8 2002 could be used as a self-supported membrane in a bolometer IR detector. Application of SU-8 does not require any advanced equipment, which makes this bolometer a rather low cost solution. A nickel resistance bolometer connected in Wheatstone bridge configuration with two variable elements has been fabricated. The detector shows a sensitivity of 9.3 V/W, when radiated with a 1.56 µm laser. A standard black matte paint was used as an infrared absorber. The absorber was applied manually and optical and thermal properties were not specified. To increase sensitivity the absorber and the application should be improved.

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