The Investigation of the Micro-heater based on MEMS Technology

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Abstract. This paper presents some information about the micro-heater based on the MEMS technology. The first part is about the materials using of the micro-heater, two different way of the formation which are the glasses and a novel polyimide are introduced. On the next part, the gas sensors are introduced because the micro-heaters are mainly used as component of the product, and different gas sensors will need different micro-hotplates. At the third part, the high-throughput methods are cited. The new research technique can help the laboratory to finish the preparing and processing quickly, and some particular skills, such as the characterization. The total essay is speaking about the micro-heater based on MEMS technology.

Keywords: MEMS Technology; Micro-heater; High-throughput Method; Improvement of the Use of Material.

1. Introduction

1.1 The MEMS Technology

1.1.1 The History of MEMS Technology

The full name of the MEMS is called "Micro-electro-mechanical systems", also written as micro-electro-mechanical systems. This technology was developed by the silicon revolution which was dated from 1959, and this is the foundation of development of mechanical systems, with the more findings of micro-machining technology based on silicon semiconductor technology. The scientists and engineers realize that this kinds of system could provide new way to interact and communicate with surroundings and process the things like chemical or motion.

The first product about the MEMS product is the resonant-gate transistor, an adaptation of the MOSFET (metal–oxide–semiconductor field-effect transistor), developed by Harvey C. Nathanson in 1965. Then more scientists were attracted by this, and did more research which enhance the practicability of the MEMS technology until now.

1.1.2 Different Field of the MEMS Technology

Because of its expansive prospect, many countries start to develop the MEMS technology so that they can let it use into different field. The major one is about sensors which can detect many different things.It includes speed, pressure, humidity, acceleration, gas, magnetic, optical, acoustic, biological, chemical and other sensors, according to the types of the main: surface array tactile sensor, resonant force sensor, micro acceleration sensor, vacuum microelectronics sensor, etc. The development direction of sensor is array, integration and intelligence. As sensors are tentacles of human exploration of nature, neurons of various automation devices, and a wide range of applications, the future will be paid attention to by all countries in the world.

1.2 The Micro-heater

It is easy to understand the meaning of the word 'micro-heater', or we can call it 'micro-hotplate', which is a kind of small high-power heaters, with precise control of temperature. Micro-heaters consist of a heat generating part connecting a metal sheath with a linear heat generating body firmly filled with a highly-pure inorganic insulator (magnesium oxide, MgO), and are composed of a sleeve whose terminal is processed for humidity-proofing and of a lead wire so that the heat generating line is completely isolated from air and gas.

1.2.1 The Features of the Micro-heater

Firstly, the micro-heater has higher range of measuring from 1000 Degree Celsius to 1900 Degree Celsius, and this is a kind of normal one, some special micro-heaters have higher range of measuring temperature. Secondly, we can know that the micro-heater is a kind of small component from its name, so that it can be used into different field easily. This assists to release the space thus more things are able to used in the product. Thirdly, the micro-heater must resist the vibration and high pressure, or we can say, it need to overcome some extreme surroundings.

1.2.2 The Miniaturization of Micro-heater

The scientists are still trying to reduce the space occupied by the micro-heater because this can bring a lot of benefits. At the top of the list, parallel manufacturing processes for large quantities can reduce the cost and time. The assembly line is suitable for micro-heater and the workers don’t need to be trained for long time. Secondly, the micro-heater connect with the integrated circuit(it is a set of electronic circuits on one small flat piece (or "chip") of semiconductor material, usually silicon.)which can make the whole system more effectively. Thirdly, as it connects to the system of the product, it helps to increase the precision of the gas detection, and even some particular micro-heater can identify the different toxic gas.

1.3 The High Throughput Method

More and more different materials are needed during the study about the micro-heater based on the MEMS technology, we need more and more different method to achieve this, and the high throughput is one of the major one.

The high throughput method means that preparing the material in a very short time. The beginning of it was in 1970, Hanak first puts forward the concept of "more sample experiment", and applied to the film in the form of binary, ternary superconducting materials research, the basic idea is through an experimental synthesis of complete coverage in the multi-component materials system composition of the sample array, using efficient means of test and analysis quickly get array of each sample in the composition, structure and performance data, Finally, the data are processed by computer and presented in an appropriate manner. However, due to the limitation of computer and other supporting technologies at that time, this method could not be popularized quickly.

1.4 Thin Firm

A film is a thin, soft, transparent sheet. Made of plastic, adhesive, rubber, or other material. The scientific interpretation of thin film is that it is a two-dimensional material formed by atoms, molecules or ions deposited on the surface of a substrate. Example: optical film, composite film, superconducting film, polyester film, nylon film, plastic film and so on. Thin film is widely used in electronics, machinery, printing and other industries.

Thin film material is a thin layer of metal or organic matter with a thickness ranging from a single atom to a few millimeters. Functional devices of electronic semiconductor and optical coating are the main applications of thin film technology.

2. Main Investigation

2.1 The Material of the Micro-heater

2.1.1 The Use of the Glasses on the Heater

During the development of materials, the element platinum has been exploited for many forms that can be used into different field, such as being an electrode. In the part of the micro-heater, Platinum also play an important role in resisting the oxidation and it can be used in a high temperature, which is at over 500 °C.

But actually, Platinum can not be used very effectively, owing to its feature--noble metal, means that it does not adhere well to materials like silicon nitride or dioxide, and the immediate between Platinum and the substrate is needed to improve by some other element like Titanium (Ti) or tantalum (Ta) which are difficult to smelt and the cost would increase a lot. They cannot achieve that adhering with Platinum easily, so that F. Biro investigated several multi-layer structures for micro-hotplate to be operated above 500 °C, such as Si, Si3N4, SiO2, TiO2, Pt, or Al2O3 layer. In addition, the micro-hotplates were mostly fabricated on the silicon or aluminium substrate. Silicon and aluminium substrates have a very high thermal conductivity, but it easily causes heat loss and power consumption.

From that kinds of situation, Wen-Yang Chang and Yu-Sheng Hsihe design a new micro-hotplate which contains glass substrate, two silicon nitride layers, a silicon oxide layer, a micro-heater layer and two electrode pads. In their speaking, the glass layer has good thermal conductivity and lower thermal expansion, which solves the problem of the silicon or aluminium substrate; SiN layer can face the high pressure caused by the higher temperature; SiO layer, which encloses the heater layer, is an electric insulator for high chemical stability. The multi-layer micro-heater is comprised of Cr, CrN, Pt, CrN, and Cr films. Finally, the electric contact pads are made Au using physical vapor deposition.

2.1.2 The Use of a Novel Polyimide

At the top of the list, we are going to introduce the polyimide. Polyimide (PI) refers to a kind of polymer containing imide ring (-Co-NR-Co--) in the main chain, which is one of the organic polymer materials with the best comprehensive performance. Its high temperature resistance is above 400°C, long-term use temperature range is -200 ~ 300°C, some of them have no obvious melting point, high insulation performance, the dielectric constant is 4.0 at 103 Hz, the dielectric loss is only 0.004 ~ 0.007, belongs to F to H insulation.

According to the chemical structure of the repeating unit, polyimides can be divided into aliphatic, semi-aromatic and aromatic polyimides. According to the interaction force between chains, it can be divided into cross-linked and non-cross-linked types.

As a kind of special engineering material, polyimide has been widely used in aviation, aerospace, microelectronics, nano, liquid crystal, separation membrane, laser and other fields. In the 1960s, the research, development and utilization of polyimide were listed as one of the most promising engineering plastics in the 21st century. Due to its outstanding characteristics in performance and synthesis, polyimide has been fully recognized as a "problem solver" for its huge application prospects, whether as structural or functional materials. It is also believed that "without polyimide, there would be no microelectronics technology today".

The main aim of this material is that reducing the the heat loss. As a new substrate, it can help to improve the heat insulation of the micro-heater. The resistive element, Au/Ti, are included in the micro-heater, and the temperature is quickly redistributed over the suspended polyimide membrane when a certain amount heating power is applied to the heater. However, the temperature change area will be irregularly, which means that some thermal energy loss during the heating, because of the effect from the radius of the membrane of the polyimide. According to the article<A novel polyimide based micro heater with high temperature uniformity>, the researchers give us a better solution: Considering the radius of the whole heating area is 1.2mm, this result is quite satisfying, the heat area will concentrate at the centre at this radius.

2.2 The Gas Sensors

2.2.1The Fabrication of the Micro-hotplate

In micro-system technology, hotplates are mainly used for sensors applications where the sensing material is deposited onto the membrane and an electrical signal is also integrated into the hotplate. By employing something films with good thermal insulation as the substrate, the micro-hotplates presents a series of advantages such as miniaturized size, low power consumption, fast response, high sensitivity, good reproduction, and feasibility of sensor array integration.

There is a new and interesting development of the material used in the some changes of the hotplates, which is silicon-on-insulator (SOI) as the substrate and metal Au as the heating electrode material. According to the research of inventors, they found that this product has new features such as lower thermal conductivity coefficient, good electrical insulation, lower thermal consumption, and obvious resistance to high temperature and lower pressure. Au, we called it Gold, can also bring a lot of advantages to this product, like its small electron mobility, stable TCR(thermal conductivity coefficient) and chemical properties.

There are two types of micro-hotplate structures: the closed-type membrane, where the membrane overlaps the silicon substrate along its periphery, and the suspended-type membrane, where the membrane is supported on the Si substrate using the supporting beams. In both cases, the membrane lies over a cavity etched in the silicon substrate. In the latter case, the thermal losses to the substrate take place only through the supporting beams and thus they are minimized compared to the closed-type membrane.

According to the information, they choose to use the suspended-type membrane structure, due to it can be used as the public heating source platform of many different narrowband infrared emitter structures, such as those based on a two-dimensional photonic crystal.

There are three kinds of heat loss way which are conduction, convection and radiation. In this new product, they need to overcome the problem such as heat conduction through the supporting beam, the conduction and convection of the air and the last one is the thermal loss brought from the thermal radiation.

They employ a variety of strategies to accomplish the goal throughout the research for the new product. The dry etching and the wet etching are the most important. In order to determine the characteristics of wet etching, they conduct an extensive corrosion experiment and analyze the principle of wet etching of silicon. The micro-bridge structures were designed to be compatible with the wet etching process.

At this period, the etching process must be introduced: in the process of making semiconductors, microelectronic integrated circuits, and micro-nanomaterials, etching is a crucial step. It is lithography's primary method of pattern processing. Photo-lithographic etching is the narrow definition of the term "etching."Photo-lithography is used to first expose the photoresist, and then other methods are used to etch the parts to be removed. Chemical or physical methods are used to selectively remove undesirable materials from the surface of a silicon wafer through etching. The primary objective is to accurately replicate mask patterns on the coated silicon wafer. In a broad sense, etching has become a general term for stripping and removing materials through solutions, reactive ions, or other mechanical methods, and a universal term for micro manufacturing with the development of micro manufacturing technology.

The design and production of a micro-hotplate using metal Au as the heating electrode material and silicon-on-insulator (SOI) as the substrate. The devices are made using dry and wet etching, magnetic sputtering, ion beam sputtering, and other IC processes. Anisotropic wet etching of silicon and thin film deposition were mainly studied.The characteristics of wet etching were analyzed through the study of the principle of wet etching of silicon and numerous corrosion experiments, and micro-bridge structures were designed to be compatible with wet etching processes. After a lot of experiments, the micro-hotplate was made with success and the optimized process for anisotropic wet etching was found for releasing the microbridge.

2.2.2 The Gas Sensor of Hydrogen

Hydrogen is a gas that is important to technology and is utilized in numerous industries.

It is utilized, for instance, as a reactant gain semiconductor process and as a feedstock in the production of methanol and ammonia. Worldwide, significant efforts have been made to extend hydrogen's use beyond traditional industrial applications due to its abundance and versatility. Hydrogen has recently been recognized as an energy storage medium that has the potential to address issues associated with fossil fuels, including air pollution, global warming, and diminishing supplies. Hydrogen is both clean and effective, with the highest energy output by weight of any chemical fuel.Additionally, significant progress has been made in the development of hydrogen-powered stationary and mobile power generators, particularly for fuel cell applications.

In the both existing and development of the hydrogen applications, the detection and the measuring the amounts of the hydrogen presents are a common need. Thus some people design a new type of the gas-sensor based on the MEMS technology. Because hydrogen is highly combustible and has a lower explosion limit (LEL) of 4% in the air, this requirement is necessary not only for life safety but also for process control of hydrogen-based energy systems. A sensor technology that can meet a wide range of requirements is required to meet these needs.Sensors must be hydrogen-selective and resistant to common impurity gases found in hydrogen feedstock for industrial applications.For real-time control of processes that operate on rapid duty cycles and life safety monitoring, a quick response time is an essential feature. Sensitivity to low hydrogen levels, a wide dynamic detection range, long-term dependability, and low power consumption are also desirable features. Additionally, sensors must be able to be produced in large quantities at a low cost.

From the straightforward addition of odorants for human identification to the intricate use of mass spectrometry, a variety of methods are currently available for the detection of hydrogen. Solid-state gas sensors can be used for continuous, multi-point applications in a number of different ways.The most common type, also known as a "catalytic combustible" or "hot wire" sensor, is made up of two resistive elements (Pt/Ir wire) arranged in a Wheatstone bridge and heated to 600–800 °C. When a flammable gas is present, the heat of oxidation raises the temperature of the one catalytically coated bead and changes the Wheatstone bridge circuit. The MOS (metal oxide semiconductor) sensor is a second type of sensor. It is made of a mixture of iron, zinc, and tin oxides that are heated to 150–350 °C. Oxygen atoms absorb on the MOS surface, which results in an equilibrium concentration of oxide ions in the layers that make up the surface. The MOS absorbs the target gases, such as hydrocarbons, H2, CO, or H2S, when they come into contact with the sensor. The material's resistance decreases as a result of this shift in oxygen equilibrium, which can be detected.MOS and catalytic sensors typically are not hydrogen-specific. A gated field effect sensor is the third one.A structure that is similar to a field effect transistor (FET) has a floating gate that is coated with a catalyst, typically palladium, in this device. The potential of the catalytic gate shifts as hydrogen is absorbed by it, modulating the channel's conductance, which is then measured.Even though this device can be very sensitive, low hydrogen levels can cause it to become saturated. A fourth sensor is based on the changes in resistivity that occur when hydrogen content in Pd or Pd alloys changes. It is common knowledge that palladium and palladium alloys change their resistivity when hydrogen is dissolved in them. In pure hydrogen, the change in resistance typically has a small magnitude, somewhere between one and ten percent.

The micro-hotplate, a novel MEMS platform-based hydrogen gas sensing technology, has been demonstrated. The sensor was functionalized by coating the micro-hotplate with a rare earth metal thin film capped by a palladium-based layer, which was made using a generic CMOS-compatible foundry process. These sensors respond extremely quickly.With a response time of less than a half a second, resistance changes of greater than 120 percent in response to exposure to 0.25 percent hydrogen concentration were recorded. These sensors detect hydrogen at concentrations ranging from 150 ppm to 1 percent and demonstrate a dynamic range of two orders of magnitude. It was demonstrated that the operating temperature of the micro-hotplate had a significant impact on sensor performance.

2.3 The High-throughput Method in Micro-heater

At the beginning, the high-throughput method should be introduced carefully, such as the fabrication skills, or the characterization of materials. In this part, the characterization of the materials would be introduced more.

First, combinatorial sample arrays or continuously composition-graded samples integrated into a relatively small area are frequently required for highthroughput characterization. As a result, the individual sample geometry is crucial; it must be small enough to be integrated and large enough to represent the targot materials' distinctive properties. The microelectronics and micro-electro-mechanical system (MEMS) industry has encouraged extensive research into the mechanical properties of thin films and nanomaterials over the past few decades. The mechanical properties of small-scale materials and structures can be tested using a variety of methods, including wafer curvature measurement, nanoindentation, micro-tensile, compression test, bulge measurement, and so on.On a single substrate, combinatorial sample arrays can be constructed and tested using some of these methods. For instance, nanoindentation is a popular method for measuring the hardness and elastic modulus of micro-scale materials. It works with both sample arrays and samples that are continuously composition-graded.

Second, combinatorial samples must be quickly tested in parallel or scanning mode for high-throughput mechanical characterization.For quick data acquisition and processing, the tools must be highly automated.In addition, nanoindentation is a well-known scanning testing method for measuring thin film materials' mechanical and tribological properties.For combinatorial samples, other existing micro-mechanical testing tools can achieve high-speed characterization with the right modifications.

Thirdly, accuracy and dependability must be ensured through careful data interpretation for combinatorial samples.When describing the mechanical properties of small-scale materials, for instance, the size effect is a well-known problem.The mechanical behavior of individual samples in the combinatorial materials library may differ significantly from that of their bulk counterparts due to their typically small dimensions.Although theoretical and experimental understanding of size effects has progressed significantly, it is still difficult to accurately correlate the outcomes of micro-mechanical testing with the actual performance of structural materials in actual applications.

2.3.1 The Resistance-temperature Dependence

The MHP(micro-hotplate)'s Pt heater's resistance-temperature dependence must be determined and calibrated in order to anneal thin films at well-defined temperatures. To measure the resistance of the Pt heater in relation to temperature, an MHP was placed inside a furnace and electrically connected. By heating the furnace at varying rates (from 0.5 K/s to 18.9 K/s) from room temperature (RT) to 670 K, the Pt heater's temperature was set externally.The furnace remained in that position for a number of hours to guarantee that the Pt heater would reach the specified final temperature. A PT 100 thermocouple, which was situated directly above the MHP, was used to measure the temperature inside the furnace. Using a digital multi-SourceMeter, the 4-point method was used to measure the resistance. The Pt thin film heaters' temperature coefficients were determined by fitting the resistance versus temperature R(T) curves with a polynomial. During the experiments, a precise calculation of the heater plane temperature is possible by utilizing these coefficients and continuously measuring the heater's resistance. During the calculations, because of the existing of the error from the accuracy of the temperature coefficients, this maximum error of 1% is negligible for the calculation of the heater temperature, which is a kind of way to adjust.

To verify the adjustment, researchers placed many temperature indicators with different melting points on the surface of the hotplates, with the observations by the light microscopy. The resistance of the Pt heater was used to determine the heater plane's temperature at the melting point of the indicator. The known indicator melting point was compared to the calculated temperature. The accuracy of the calibration was assessed using the difference between these two temperatures. Therefor, the low adhesion of the bulk indicator grains and the temperature distribution across the heater plane during heating may account for the variation in the observed melting points.

2.3.2 The Uniformity of the Heater Temperature

An infrared thermo camera was used to further characterize the heater plane's temperature distribution.These measurements were carried out on a variety of heater designs with the intention of locating the one that provided the most uniform temperature distribution.The maximum temperature difference in ambient air between the center and the edge of the current best design is T = 42 K.The heater design with the most in-homogeneous heater plane, on the other hand, had a temperature difference in the surrounding air of T = 70 K.Convection and conduction through the air are the primary loss factors for temperature in ambient air conditions, but these losses are negligible in a vacuum.Radiation is the primary cause of this loss.However, the heat conduction of a thin metallic film deposited on the heater will uniformize the temperature distribution.The area of the thin film that is deposited ought to be reduced in order to further enhance the temperature uniformity across the heating plane.The temperature gradients that exist at the edge of the heating plane in comparison to the center are lessened as a result of this reduction in the deposition area.

2.3.3 The Temperature-time Behaviour

The Pt meander was heated to a final temperature and its resistance was measured as a function of time to determine the heating rate. By heating the MHP to a starting temperature and maintaining that temperature for a few seconds, the cooling rate of the MHP was examined. After that, while measuring the heater resistance over time, the electrical power used to heat the Pt meander was turned off. The temperature difference divided by the time difference was used to calculate both the heating and cooling rates. A MHP's temperature-time dependence was examined both in an ambient setting and in a vacuum chamber with a pressure of p 3 106 mbar. The room temperature (RT = 299 K) was used as the reference temperature for calculating the heating and cooling rates.

3. Conclusion and Outlook

The aim that I start to investigate the micro-heater based on the MEMS technology, is that I found that the MEMS technology is a new product in the era, and it is accord with my assumptions of the future, which is the miniaturization of everything. And also I was very interesting about the mechanic, thus I choose this project. After the investigation, I think that the MEMS technology would be more and more common in the future, not only the micro-heater, but also including other technology, e.g. accelerator. At the same time, this technology would be common in the normal life. The scientists are trying to make these small products more intelligent, and the improvement of the materials is also important. Profit from the 3D printing, a lot of processing problem can be solved.

References

[1] Yi, X., Lai, J., Liang, H., & Zhai, X. (2011, February). Fabrication of a MEMS micro-hotplate. In Journal of Physics: Conference Series (Vol. 276, No. 1, p. 012098). IOP Publishing.

[2] Shifeng Yu, Shuyu Wang, Ming Lu, Lei Zuo, A novel polyimide based micro heater with high temperature uniformity, Sensors and Actuators: A Physical http://dx.doi.org/10.1016/j.sna.2017.02.006.

[3] DiMeo Jr, F., Chen, S., Chen, P., Neuner, J., Roerhl, A., & Welch, J. (2006). MEMS-based hydrogen gas sensors. Sensors and Actuators B: Chemical, 117(1), 10-16.

[4] Zhang, X., & Xiang, Y. (2017). Combinatorial approaches for high-throughput characterization of mechanical properties. Journal of Materiomics, 3(3), 209-220.

[5] Chang, W. Y., & Hsihe, Y. S. (2016). Multilayer microheater based on glass substrate using MEMS technology. Microelectronic Engineering, 149, 25-30.

[6] Hamann, S., Ehmann, M., Thienhaus, S., Savan, A., & Ludwig, A. (2008). Micro-hotplates for high-throughput thin film processing and in situ phase transformation characterization. Sensors and Actuators A: Physical, 147(2), 576-582.

[7] Li, X., Huang, Y., Chen, X., Xu, X., & Xiao, D. (2018). Electro-thermal analysis of an Al–Ti multilayer thin film microheater for MEMS thruster application. Microsystem Technologies, 24(5), 2409-2417.