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Ion beam sputtered Ge–Si–O amorphous thin films for microbolometer infrared detectors and their application in earth sensors

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ABSTRACT

Ge–Si–O thin films are prepared by ion beam sputtering technique with argon (Ar) alone and argon and oxygen as sputtering species, using sputtering targets of different compositions of Ge and SiO_2. The deposited thin films are amorphous in nature and have chemical compositions close to that of the target. The study of electrical properties has shown that the activation energy and hence the thermistor constant (β) and electrical resistivity (ρ) are sensitive to oxygen flow rate, and they are the least for thin films prepared with Ar alone as the sputtering species. Different thermal isolation structures (TIS), consisting of silicon nitride (Si_3N_4) membrane of different thicknesses, Ge–Si–O thin film and, chromium coating on the rear side of the membrane, are prepared by bulk micro-machining technique, whose thermal conductance (G_{th}) properties are evaluated from the experimentally determined current–voltage (I–V) characteristics. G_{th} shows non-linear dependence with respect to raise in temperature of thin film thermistor due to Joule heating. The infrared micro-bolometer detectors, fabricated using one of the TIS structures have shown responsivity ($\Re$) close to 115 V/W at a bias voltage of 1.5 V and chopping frequency of 10 Hz, thermal time constant (τ) of 2.5 ms and noise voltage of 255 nV/Hz$^{1/2}$ against the corresponding thermal properties of G_{th} and thermal capacitance C_{th} equal to 9.0×10^{-5} W/K and 1.95×10^{-7} J/K respectively. The detectors are found to have uniform spectral response in the infrared region from 2 to 20 μm, and NEDT in the range from 108 to 574 mK when used with an F/1 optical system. The detector, in an infrared earth sensor system, is tested before an extended black body which simulates the earth disc in the laboratory and the results are discussed.

1. Introduction

Uncooled micro bolometer infrared (IR) detectors find widespread use in several areas such as automotive industry, medical instrumentation, high temperature material processing, defense and space science and technology. The space science and technology demand simple uncooled infrared detectors, in a wide range of infrared instruments for applications in remote sensing [1], and attitude determination of low and medium earth orbit and geo-stationary/geo-synchronous satellites [2]. The IR horizon earth sensors, belonging to scanning and conical scanning categories, make use of un-cooled immersed bolometer IR detectors in which thermistor flakes, fabricated by a ceramic process are immersed on a hemispherical germanium (Ge) lens. Such a configuration mandates an inevitable application of a high voltage bias in order to obtain high responsivity [3]. But application of a high voltage, continuously over a longer duration of time, across the thermistor flake gives scope for undesirable electrical short circuit through micro-defects in thermal impedance layer which initiates failure of the detectors quite often [4,5]. This calls for the use of thermistor bolometer detectors which can operate at a lower bias voltage, yet capable of showing higher signal responsivity and speed of response. Such features are invariably required in order that the space borne sensor systems operate with a high degree of reliability. These novel features can be envisaged by the use of efficient thin film thermistor sensors on novel thermal isolation structures which have very low thermal mass and tailored thermal conductance and capacitance. It is needless to emphasize that the noise of resultant sensor structures should be as low as possible.

The advent of thin film and micro-machining technologies and their application for development of micro-bolometer IR detectors [1,6–9] have scope to achieve the above desired detector properties. There are three micro-bolometer detector configurations based on pixel density, which are of interest in space, defense and terrestrial applications [2,10,11], namely (1) dual element detectors, (2) linear array with lower pixel density (16 × 2 or 32 × 2) in a staggered manner and (3) complex linear and area arrays with high pixel density (256 × 1, 512 × 3, 320 × 240 and 512 × 512). While the first two detector configurations can be produced using less expensive

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bulk micro-machining techniques, in combination with thin film thermistors technologies, the latter one is possible only by surface micro-machining techniques. However, it may be noted that all the three detector configurations are of equal importance in the current infrared sensors and their use in space, defense and terrestrial applications. One of the objectives of the present investigation is to study the usefulness of simple dual element detectors in infrared horizon earth sensors in which immersed bolometer detectors are being currently used. It is needless to emphasize the importance of micro-bolometer technologies from the point of view of high volume of production, at lower cost and better scope for integration with signal processing electronics [8,12–15].

The sensor elements used in micro-bolometer IR detectors are resistive in nature which generally have a high temperature coefficient of resistance (TCR). Many high TCR materials have been used such as vanadium oxide (VO_x) [16–20], yttrium barium copper oxide (Y–Ba–Cu–O) [21–27], poly silicon [6,28], and manganese oxide doped with nickel and cobalt oxides (Ni–Mn–Co–O) [10,29]. However, germanium–silicon–oxide, which is abbreviated as Ge–Si–O, is also emerging as a potential candidate for the development of micro-bolometer IR detectors because of its high TCR and compatibility to CMOS process [30,31]. The studies carried out so far have focused on preparation of Ge–Si–O thin films by electron beam evaporation and RF sputtering and their application in micro-bolometer infrared detector [30–32]. However, there are hardly any studies on thermistor properties of Ge–Si–O thin films, which are prepared by ion beam deposition from Ge–Si–O targets of different compositions and their applications in development and characterization of micro-bolometer IR detectors. Also there are no investigations on (1) thermal conductance property of thermal isolation structures (TIS) and its dependence on the configuration of TIS, (2) responsivity of Ge–Si–O thin films based micro-bolometer detector in different infrared spectral regions, (3) role of membrane thickness of TIS on frequency response characteristics and (4) application of the micro-bolometer detectors in specific space-borne infrared instruments.

In this paper, preparation of thin film thermistors from Ge:SiO_2 targets by ion beam sputtering technique is presented first followed by experimental details on fabrication of micro-machined thermal isolation structures and there from packaging of micro-bolometer infrared detectors. Later, thermo-electric properties of Ge–Si–O thin films and thermal conductance properties of Ge–Si–O thin films deposited on different micro-machined thermal isolation structures are discussed. Then, the paper is devoted to the results of detector properties, namely responsivity, time constant, detectivity and noise equivalent temperature difference NEDT, and results of application of the detectors in infrared earth horizon sensors.

2. Experimental

2.1. Preparation and characterization of thin film thermistors

Thin films of Ge–Si–O are deposited using an ion beam deposition (IBD) system (Oxford Instruments, UK) equipped with a three cm Kaufmann ion source, a suitable pumping system consisting of a turbo-molecular pump backed by a rotary pump and an in situ quartz crystal sensor. The 100 mm diameter targets of different compositions namely, SiO_2–Ge (15:85) and SiO_2–Ge (20:80) are considered in the present investigation and they have been procured from Vin Karola Instruments, USA. Typically 15:85 ratio corresponds to the percentage ratio of silicon di-oxide and germanium by weight and the purity of the targets, is better than 99.96%. For preparation of Ge–Si–O thin film thermistors, two types of substrates are employed, namely oxidized Si wafers (orientation: (1 0 0)) by wet oxidation technique (oxide thickness ~ 1000 nm) and silicon nitride (Si_3N_4) coated Si wafers of (1 0 0) orientation, by low pressure chemical vapor deposition (LPCVD), from SPI Supplies, USA. The size of each substrate is 25 mm × 25 mm. While thermistor sensors deposited on oxidized Si wafers are used for characterization of electrical properties of thin film thermistors, thin films grown on Si_3N_4 coated Si wafers are used for micro-bolometer IR detectors' development and characterization. This scheme of electrical characterization was adopted only after ensuring that there are no differences in electrical properties between the two sets of samples, namely thin films deposited on oxidized silicon wafers and Si_3N_4 coated silicon wafers. In order to vary the thermal properties of TIS, Si wafers coated with different thicknesses of Si_3N_4 layer, namely 500 nm, 200 nm and 100 nm are used, the basis of which will be evident from the results and discussion presented in the next section.

Table 1
Deposition parameters of Ge–Si–O thin film thermistors.

Parameter	Parameter value
Base chamber pressure	$<4\times10^{-6}$ mbar
Pressure during sputter deposition	$<4\times10^{-4}$ mbar
Beam voltage and current	1000 V and 35 mA
Discharge voltage and current	36 V and 1.2 A
Neutralizer current	45 mA
Accelerating voltage and current	−125 V and 2.0 mA
Deposition rate	0.06–0.08 nm/s
Deposition thickness	500 nm
Substrate temperature	Room temperature
Substrate-to-target distance	14 cm
Sputtering species	Argon and oxygen

The Si wafers are cleaned using an analytical grade isopropyl alcohol in an ultrasonic cleaner and dried using a high purity dry nitrogen. Then the wafers are loaded onto a substrate holder located in the ion beam chamber. Thin films of Ge–Si–O are deposited using an Ar ion beam of energy one kilo-electron volt (keV) with or without oxygen. It is required to be noted that in this investigation two types of thin films, namely Type I and Type II, are prepared from sputtering targets of compositions 15:85 (SiO_2:Ge) and 20:80 (SiO_2:Ge) respectively. For preparations of these thin films, the deposition parameters presented in Table 1 are followed. During thin film growth, the flow rate of argon (Ar) gas is maintained at 4 sccm and the flow rate of oxygen (O_2) gas is varied from 0 to 2.5 sccm to prepare thin films of Ge–Si–O under different oxygen concentrations. The flow rates of Ar and O_2 are separately controlled using mass flow controllers, from Brooks, UK, which have been calibrated *a priori*. During deposition, the thickness is monitored using a quartz crystal monitor, from Inficon, USA, and the coated thickness is about 500 nm which is verified using an optical profilometer, Model Wyko NT1100 from Veeco, USA.

The elemental composition and surface morphology of deposited thin films of Ge–Si–O are analyzed using a scanning electron microscope (SEM) from, JEOL, USA, as per the standard procedure. For elemental composition analysis, an energy dispersive X-ray analysis (EDAX) probe of the SEM is used. The crystalline structure of thin films is investigated using an X-ray diffractometer, Model XPERT-PRO from PANalytical, the Netherlands. Further the sheet resistance of thin films is measured using a four probe sheet resistance measurement instrument, Model CMT-SR2000NW from AIT Korea. The electrical resistance of thin films is measured at different temperatures, ranging from 303 to 383 K by means of a high resistance meter, Model 6517B from Keithley, USA, to an accuracy better than 1% over the nominal value. The temperature of the sample is monitored and varied by means of a setup consisting of a K-type thermocouple and a heater, which can heat the sample over the required temperature range. The sample temperature is measured and controlled to an accuracy better than ±0.5 K. The heater is