Advantages and Limitations of Diamond-Like Carbon as a MEMS Thin Film Material

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ABSTRACT

Combining Bulk Silicon Micromachining (BSM) with Diamond-Like Carbon (DLC) thin film technology can be favourable used to make high performance MEMS devices. We highlight the versatility of BSM combined with the unique features of our proprietary DLC thin film technology to make high performance MEMS devices at favourable cost. A high performance infrared emitter has been designed and commercialised, with the most distinctive features being high speed with a modulation depth of more than 100 HZ, broadband IR emission from 1 to 20 micrometers, more than 10% power efficiency, and a lifetime beyond 100,000 hours. These emitters are already in use in system applications like non-dispersive infrared gas sensors.

1 INTRODUCTION: MEMS STRUCTURES WITH DIAMOND-LIKE THIN FILMS

We assume here that the versatility of bulk silicon micromachining is well know, and in addition we can observe from the material properties of Diamond-Like Carbon (DLC) that one or more of the following characteristics can be favourable exploited to make MEMS structures and/or devices with DLC thin films:

- Extraordinary Yield Strength of up towards 30 times better than stainless steel and up to 5 times better than silicon.
- Extraordinary stiffness with Young Modulus of Elasticity of around 8 times stiffer than silicon and around 7 times stiffer than steel.
- Indentation hardness and wear resistance approaching diamond, the best among any other materials.
- High thermal conductivity.
- Superior chemical and corrosion resistance
- Processing of DLC films compatible with most silicon processes up to 500 °C ((short pulsing to ~800°C).
- DLC thin films can be made by different Physical Vapor Deposition and Chemical Deposition Methods, or combined methods.
- Combination of silicon MEMS with DLC thin films can be used to make devices combining the versatility of silicon processing with the unique features of DLC thin film

If one of more of these features can be exploited together with silicon MEMS technology such as Bulk Silicon Micromachining, the resulting BSM/DLC mixed technology can be used to make very competitive MEMS devices, such as the infrared emitter described here and shown in Figure 1.

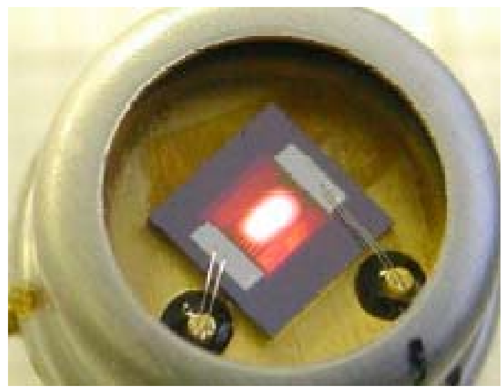

Figure 1: Picture of the BSM/DLC based infrared emitter packaged in a metal can transistor header. The picture is taken during operation, showing the visible part of radiation from the emitting membrane.

2 DIAMOND-LIKE THIN FILM PROCESSES

We have developed the following DLC thin film processes that can be combined with silicon MEMS technologies:

A Pulsed Cathodic Arc (PCA) process, a physical vapor deposition process for producing ultra-hard amorphous diamond (AD) carbon coatings. These materials, also called tetrahedral amorphous carbon (ta-C), consist essentially of pure carbon, with only a trace of hydrogen (~90 % sp^3 bonding). The AD coatings have extreme hardness (70-80 GPa), close to that of crystalline diamond. The process can be scaled to coat substrates of an arbitrary size at high rates and low cost. The first application is as protective coatings in places of severe wear or corrosion. The process is flexible—multiple independent sources can be mounted in any direction—and has high deposition rate capability. The films produced with PCA are generally denser and of higher quality than films produced with other vacuum deposition technologies. Exceptional adhesion is achieved with a proprietary process. Intex has developed a deposition process that results in stress-free AD films for use as structural elements such as membranes and cantilevers. Figure 2 shows a micrograph of an AD film conformally coated on a WC substrate.

A NanoAmorphous Carbon (NAC) process, giving a new class of multi-functional electronic materials, coatings, with conductivity that can be varied from dielectric to metallic. The films are obtained by Plasma Enhanced Chemical Vapor Deposition (PECVD). The PECVD-produced film is an amorphous dielectric with a composition consisting of a substantially sp^3-bonded carbon network that also contains silicon and oxygen. NAC films can be made electrically conducting by incorporating metals into the carbon matrix by a simultaneous sputtering process, or Plasma Enhanced Physical Vapor Deposition (PVD) The resistivity of the film is controlled by controlling the metal concentration. The conductivity reaches a maximum of ~10^4 S/cm. Dielectric films (without conducting additives) have conductivities in the 10^{-10} S/cm range. This is a larger range of conductivity than has been observed with any other known material.

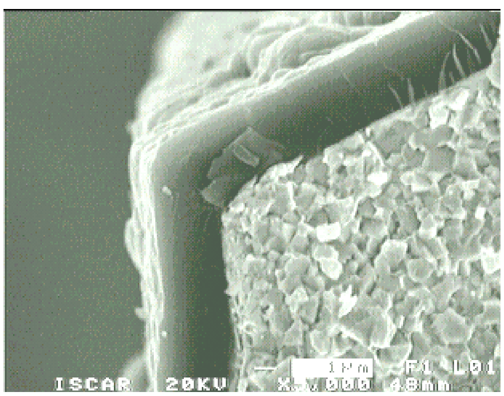

Figure 2: Micrograph of a ~3 micrometer amorphous diamond carbon on sintered tungsten carbide.

Processing in air is normally limited to 350°C - 400°C. NAC, which is a mixture of SiO_x and DLC-type of material is more stable. Short pulsing up to ~800°C is possible, and sustained processing can be done at 500°C. The principle of operation for NAC deposition system with combined Plasma Enhanced Vapor Deposition (PECVD) and Physical Vapor Deposition (PVD) is shown in Figure 3.

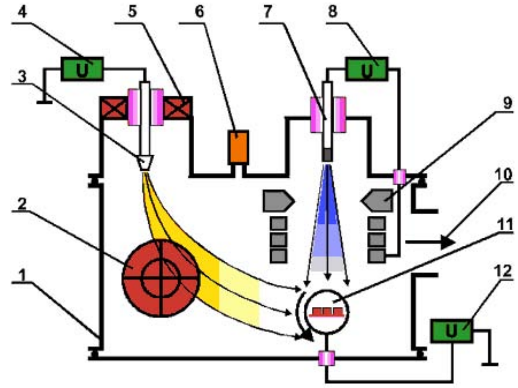

Figure 3: Schematic representation of the Intex Pulsed Cathodic Arc deposition system for producing strongly adhering AD films. (1) Vacuum chamber; (2) deflecting magnetic system; (3) metal plasma source; (4) power supply unit; (5) focusing magnetic system; (6) manometer; (7) pulsed plasma accelerator cathode; (8) power supply unit; (9) pulsed plasma accelerator anode; (10) vacuum pumping; (11) carousel with substrates; (12) substrate bias voltage.

The conductivity of the NAC film can be controlled by the atomic fraction of a metal as the conductive additive, as shown in Figure 4 with tungsten (W) as the metal additive.

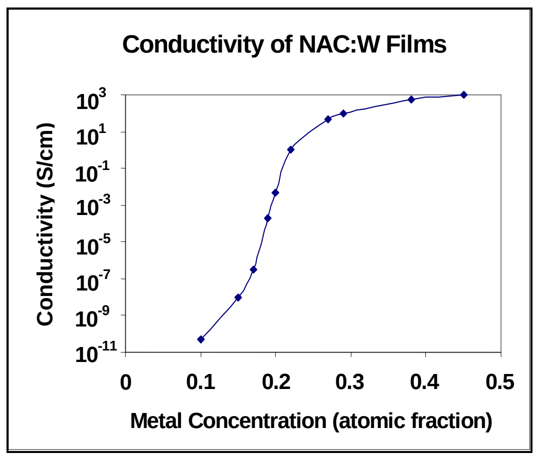

Figure 4: Conductivity of the NAC film as a function of the atomic fraction of tungsten as the metal additive cosputtered during the NAC deposition process.

3 THE EMITTER MADE BY SILICON BULK MICROMACHINING AND DIAMOND-LIKE CARBON THIN FILM TECHNOLOGY

The versatility of the NAC process in combination with silicon MEMS process technology is demonstrated by a broadband infrared emitter. Intex and its subsidiary Patinor Coatings have developed a micromachined pulsed infrared light source with high intensity and ability to pulse at high frequencies. The IR emitter incorporates a NAC film as a thermoresistive element in the form of a free-hanging thin multilayer membrane supported by silicon (Figure 5). The emission spectrum is that of a greybody and provides a wide spectral output, from 1 μm up to 20 μm. The high emissivity, high thermal conductivity, low thermal mass and high strength of the NAC material allow rapid heating and cooling by passing an alternating current through the resistive membrane. The resistivity of the NAC material is controlled by cosputtering of a metal additive.

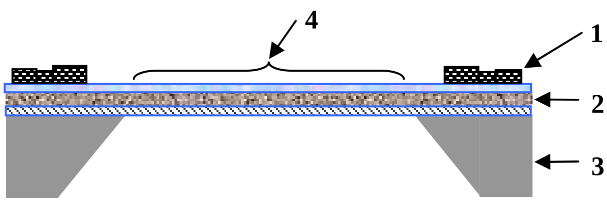

Figure 5: Cross section view of the emitter chip: 1) Bonding pads; 2) NAC multilayer membrane, 3) Silicon support, 4) Active emitter area.

The source can pulse at frequencies up to 100Hz at ~50% modulation depth. High frequency pulsed sources are important for achieving good signal-to-noise ratios (high sensitivity) in IR gas sensors. The IR emitters are fabricated using MEMS technology and can be tailored to the customer's requirements over a wide range.

The emitter is now in production with the following most distinctive typical specifications:
Chip Size: 3.7 mm x 3.7 mm
Spectral Output Range 1.0 – 20 micrometer
Emitter Surface Area 1.7mm x 1.7 mm^2
Resistance 50 Ω
Drive Voltage (pulsed, bi-polar or DC) 6.5 V
Drive Current 135 mA
Working Temperature 750 °C
Modulation frequency 0 – 100 Hz
Maximum Frequency at 50% Modulation 100 Hz
Power Consumption 900 mW
Integrated Power Emission 90 mW
Warm-up Time <30 msec
Decay time <5 msec
Lifetime >5,000 hours at 750°C
>25,000 hours at 600°C
>100,000 hours at 500°C

In Figure 1, the emitter is shown packaged in I TO-5 type of metal can header, with an open header cap. The cap can alternatively be sealed in nitrogen with a filter window like calcium fluoride, sapphire, silicon etc., depending upon the spectral properties wanted for the cap window.

In Figure 6, the pulsing speed of the emitter is shown as the modulation depth at 50% duty cycle, showing that the emitter can be modulated beyond 100 Hz.

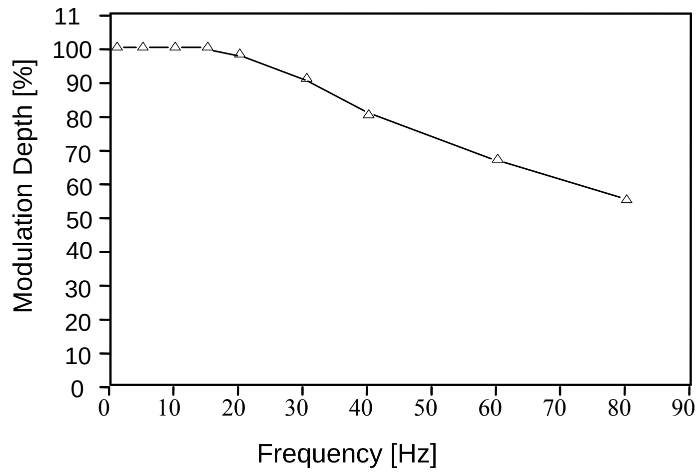

Figure 6: Modulation depth measurement for the infrared emitter at 50% duty cycle.

The temperature distribution across the area of the emitter membrane is shown in Figure 7 at a working temperature of approximately 750 °C at the centre of the membrane, showing the effect of sideways conduction cooling to the silicon frame of the emitter.

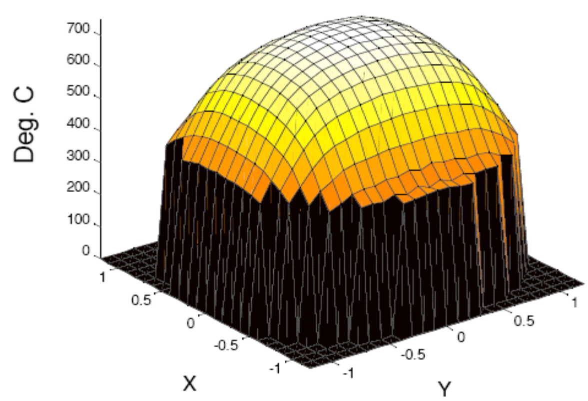

Figure 7: The temperature distribution across the emitter membrane. X and y coordinates in mm.

The emitter output can be focused with a parabolic reflector mounted on the header cap, as shown in Figure 8, Figure 9 and Figure 10. In this way, improved signal-to-noise ratio can be achieved for the same power input to the emitter.

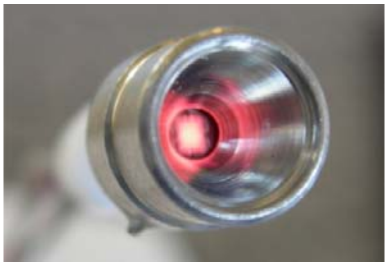

Figure 8: Picture of the emitter with the parabolic reflector mounted on the header cap.

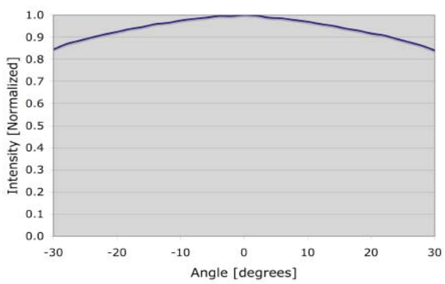

Figure 9: Angular distribution of infrared radiation without parabolic reflector.

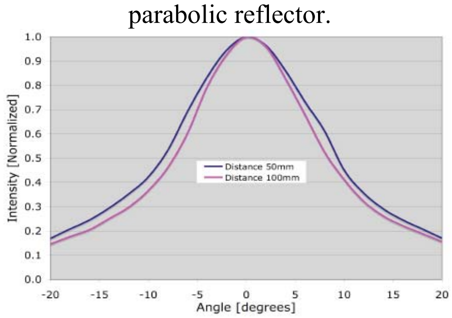

Figure 10: Angular distribution of infrared radiation with parabolic reflector.

The IR emitters can be used as the light source in infrared gas sensors for industrial, consumer, research and medical applications, mostly based upon the non-dispersive infrared sensing principle (ND-IR) Application examples are: Explosive gas detection systems (methane); combustion efficiency and stack emissions monitoring systems (CO, , CO_2); toxic emission systems (SO_x, NO_x, NH_3); air quality monitoring systems; HVAC efficiency (controlling airflow by measuring CO_2 concentration); spectrophotometers; patient bedside monitoring systems; anesthesia gas monitoring systems (CO_2 and anesthetic gases); noninvasive glucose measurements; automotive engine control and exhaust monitoring; and chemical warfare agent detection.

4 CONCLUSIONS AND FURTHER WORK

We have explained and demonstrated that Bulk Silicon Micromachining and Diamond-Like Carbon Thin Film Technology can be combined to make versatile MEMS devices. The demonstrator device is an infrared emitter with high speed, broadband infrared emission spectrum and high power efficiency as distinctive features. This emitter is already in production, to be ramped up to high volumes the coming years. In the future, other MEMS devices will be developed, which can benefit from these mixed technologies.

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