CMOS Terahertz metamaterial based 64 x 64 bolometric detector arrays

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***Abstract*—We present two terahertz detectors composed of microbolometer sensors (vanadium oxide and silicon pn diode) and metamaterial absorbers monolithically integrated into a complementary metal oxide semiconductor (CMOS) process. The metamaterial absorbers were created using the metal-dielectric-metal layers of a commercial CMOS technology resulting in low-cost terahertz detectors. The scalability of this technology was used to form a 64 x 64 pixel terahertz focal plane array.**

I. INTRODUCTION

CMOS technology has become the preferred method for the production of high resolution digital cameras due to the advantages on offer such as compact size and reduced cost via mass production manufacturing. The development of CMOS compatible detectors in other wavelengths, besides the visible spectrum, has expanded to the production of infrared (IR) cameras however it is yet to be exploited in the terahertz (THz) region. The importance of THz waves relies on its unique characteristics such as: transparency to many non-conductive materials; it is non-ionizing thus safe to biological tissue; has better spatial resolution than millimeter waves; and substances have unique THz spectral signatures which can be identified via THz spectroscopic methods. Therefore, THz waves are promising to relevant applications in sectors such as quality control, defense and security [1] as well as biological and medical imaging [2].

Adoption of these applications into everyday life has been hampered by the lack of inexpensive, compact and room-temperature THz sources and detectors. Further development of THz sources and detectors would bring THz technology on par with its electromagnetic (EM) neighbors, IR and microwave waves. In this paper we demonstrate the development of uncooled, low-cost and compact THz detectors composed of microbolometers and metamaterial (MM) absorbers monolithically integrated into a CMOS process. MMs were implemented due to the lack of natural materials that absorb THz frequencies. MMs are subwavelength periodic arrays whose EM properties are determined by the size, shape and structure rather than their physical composition. Their metal-insulator-metal construction lends itself to integration into the layers of a commercial CMOS process. This concept was implemented in a 180 nm six-metal layer process from Texas Instruments (CMOS9t5V). Broadband THz MM absorbers with cross-shaped electric ring resonators (ERRs) were integrated in the top three metal layers (M4 to M6), the ground plane was in M3 and the lower two metal layers were used for the readout electronics interconnect.

Thermal sensors commonly known as microbolometers are widely used to detect IR radiation. The most common detector materials are amorphous silicon (α-Si), vanadium oxide (VOx) and silicon (Si) pn diodes. They are used due to their ability to detect incident radiation without the need of cryogenic cooling. Microbolometers quantify the radiation intensity by measuring the voltage change with the help of integrated electronics. The IR techniques were translated to THz detectors by integrating microbolometers in each pixel of the array. VOx and Si pn diodes were integrated with the MM absorbers to realize two different types of monolithic THz detectors operating at 2.5 THz.

II. RESULTS

The two types of THz detectors, VOx and Si pn diode, are composed of three ERRs and a ground plane separated by the respective insulating layers (metal-dielectric-metal structure). In simulation, the broadband MM absorber had a broad absorption peak centered at 2.65 THz of 88.2% and experimentally it had two absorption peaks at 2.78 THz and 2.52 THz of 71.4% and 56.4% respectively. Since our frequency of interest is 2.5 THz the experimental results confirmed that the broadband MM structure absorbs more than 50% at the required frequency. Each pixel contains the broadband MM absorber, its respective microbolometer (VOx or three Si pn diodes in series) and routing electronics for reading the output voltage. Both detectors were characterized to determine the relevant figures of merit: Responsivity (R_v), Temperature Coefficient of Resistance (TCR) or Voltage (TCV), Noise Equivalent Power (NEP) and thermal time constant (τ). The detectors were originally characterized as received from the foundry without creating membranes (308 μm thickness). In order to improve the detectors' performance, the underlying silicon underneath the pixels was etched using a standard dry etch process to create thin membranes to minimize thermal capacitance, thus reducing the thermal time constant and improving the detector responsivity. The performance of the VOx and Si pn diode detectors is compared in Table 1 for unetched and etched membranes.

Figures of Merit	**VOx** [3]	**Si pn** [4]
TCR/TCV	-2 %/K	-5.4 mV/K
DC R_v (unetched silicon)	6.7 kV/W (308 μm - 600 nA)	78.9 V/W (308 μm - 10 μA)
DC R_v (thinnest membrane)	32.6 kV/W (8 μm - 600 nA)	683.7 V/W (9 μm - 10 μA)
AC R_v (thinnest membrane)	59 kV/W (1 Hz - 2 μA)	274 V/W (1 Hz - 10 μA)
NEP	108 pW/√Hz (15 Hz)	10.4 nW/√Hz (5 Hz)
τ	68 ms	420 ms

Table 1. Figures of merit comparison from both THz detectors.

It can be concluded from the results that the VOx sensor of 8 µm membrane thickness outperforms the Si pn diode in terms of response, NEP and speed response mainly due to its larger temperature coefficient, -2 %/K vs -5.4 mV/K (from three diodes in series). For example: a 1-degree change in temperature would result in a -30 mV change for a VOx resistance of 15 MΩ biased at 100 nA in comparison to a -5.4 mV change for the Si pn diode sensor. The latter sensor could be improved by increasing the number of diodes in series although this would increase the pixel size and in turn increase the thermal capacitance resulting in a slower sensor.

Single pixel imaging experiments were performed with both THz detectors in transmission and reflection mode proving the capability of these technologies and THz for imaging hidden objects [5]. In this paper we show an example of an imaging experiment in reflection mode realized with the VOx sensor via raster scanning methods. For this experiment, the VOx sensor was biased at 200 nA using a Keithley 4200-SCS source measure unit (SMU) and the incident beam was modulated with an optical chopper set at 1 Hz. The source had an average power of 30 mW focused on the object. The detector was positioned at a 30° angle from the metallic object that was placed on an x-y-z stage. The object was scanned with a 0.5 mm x 0.5 mm resolution covering a total area of 20 mm x 20 mm. The output voltage was obtained from the reflected THz signal on the surface of the object and a 2D image was acquired by xy raster scanning the object using Labview software. An optical micrograph of the metallic object, along with its dimensions, is shown in Fig. 1a and the captured THz image is shown in Fig. 1b. The non-uniformity of the THz image, in terms of voltage intensity, was caused by the power instability of the CO_2 pumped CH_3OH gas laser source used to illuminate the object.

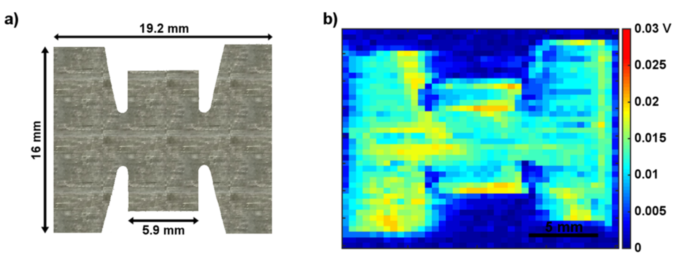

Fig. 1. a) Metallic object used for reflection imaging and b) captured 2.5 THz image in reflection mode of the metallic object.

The performance of the detectors can be improved by reducing the volume of the pixel thus decreasing the response time, operating the detector under vacuum to reduce the NEP, and optimizing the MM absorber structure to obtain perfect absorption at the appropriate active imaging frequency.

The concept of creating high resolution FPAs was investigated by scaling the detector with the best performance into a 64 x 64 FPA. A false color scanning electron micrograph (SEM) of a section of the FPA is shown in Fig. 2a. The image also shows the surface profile indicating the heights on each section of the array. The bluest areas indicate the surrounding etched material in each pixel (40µm pitch). This was done in order to create free standing membranes to avoid thermal cross-talk between pixels. Each pixel shows the top most ERR, VOx sensor in an '*L*' shape and vias connecting to the readout electronics in the lower layers of the CMOS process. The 64 x 64 focal plane array (FPA) was characterized using a 50 nA bias current and the voltage outputs of each pixel resulted in the voltage map shown in Fig. 2b. The non-uniformity could be caused by defects introduced during the post-processing steps, mismatch in the electronics or VOx film resistance. External image processing can compensate for this variability.

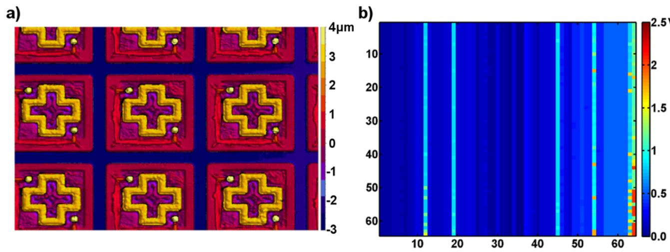

Fig. 2. a) False color scanning electron micrograph of a section of the 64 x 64 FPA and b) voltage map of the THz 64 x 64 FPA.

There are many advantages of this technology starting from its low-cost production, small portable size, easy integration and its scalability allowing for the creation of higher resolution FPAs. Additionally, the MM structures can be designed to absorb at frequencies from the millimeter wave to the visible. This can be achieved by modifying the shape, width and length of the ERRs allowing the technology to be implemented in other wavelengths. Furthermore, this technology has the potential to be integrated with visible plasmonic filters to render coaxial imaging for visible and THz frequencies.

III. Summary

We have coupled CMOS THz MM absorbers with uncooled microbolometers, VOx and Si pn diode, to realize THz detectors. The technology advantage of scalability makes it suitable for low-cost and high resolution FPAs (e.g. 64 x 64). This technology allows transmission and reflection mode imaging. Furthermore, the operating frequency of the MM absorber can be tuned from the millimeter wave to visible wavelengths by simply modifying the unit cell size and ERR dimensions [6]. This could result in coaxial imaging of different wavelengths in order to render more data rich images.

References

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