Technion Israel Institute of Technology

VLSI Lab

Department of Electrical Engineering

Thermal Antenna for Passive THz Security Screening System and Current-Mode Active-Feedback Readout Circuit for Thermal Sensor

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1. Background

THz frequencies occupy a small window between optical infrared waves and mm/radio waves. So far, the THz region of the spectrum has not been explored extensively due to lack of solid state devices operating at this frequency (as sources or detectors). The goal of this project was to design a model for a pixel for a THz frequency camera based on passive thermal sensor, and a readout integrated circuit (ROIC) that reads and amplifies the current from an array of pixels for a purpose of making a monolithic security intruder camera integrated on single die.

A thermal sensor for passive THz frequency is considered to be a breakthrough in imaging sensors technology since its high penetration- through fabric, paper, wood, plastic, certain stone materials and dust. THz sensors can be used in security cameras, airport security screening systems, medical applications like detecting malignant tumors under the skin and more. The human body emits black body radiation of THz whose effective detection distance is currently approximately 10 meters.

The relative advantage of THz frequency, for the purpose of its intended use in this project, is that it in non-ionizing radiation. In other words, its photons are not energetic enough to break chemical bonds or ionize atoms or molecules, which is the main reason why higher energy photons such as x-rays and UV rays are so dangerous. In addition, THz radiation has high penetration into a wide variety of non-conducting materials unlike microwave and infrared. Therefore even if THz sources were to be used, the system still be health-safe.

The THz sensing is based on a combination of suspended TeraMOS transistor and thermal antenna fabricated using a CMOS-SOI process implemented using MEMS post processing techniques. These ideas aim to exploit leading edge technology and required confronting and overcoming many challenges.

2. Pixel and Array Structure

The THz focal plane array (FPA) comprises an array of pixels based on **FSS** (frequency selective surface) model. FSS is an array of unit cells whose geometric arrangement defines a fully symmetric and repetitive structure. An important property of this surface is that it creates a band stop filter, absorbing the targeted frequency with very high efficiency.

Each pixel (unit cell) is built from an antenna made from 2-4 transistors (depending on the type of pixel) connected in series. A reflector is located below the antenna built from a perfect conductor, creating an optical cavity structure for maximum absorption of the radiation. This optical cavity enables the antenna to absorb the THz radiation while entering and exiting it, due to a destructive interference of the transmitted wave and the reflected wave from the grounded plane. Each pixel is packed in vacuum and therefore does not need cooling. The unit cells are arranged in a periodic array to form a fully symmetric and repetitive structure (Fig 2c).

3. System Architecture

When black body THz radiation enters the pixel, it impacts the antenna and is absorbed in the TeraMOS transistors thus changing the current from the bias current. The antenna is located in the center of the pixel, connected to a supporting arm. This current goes through the supporting arm and enters to an integrated circuit which amplifies the signal before further image processing.

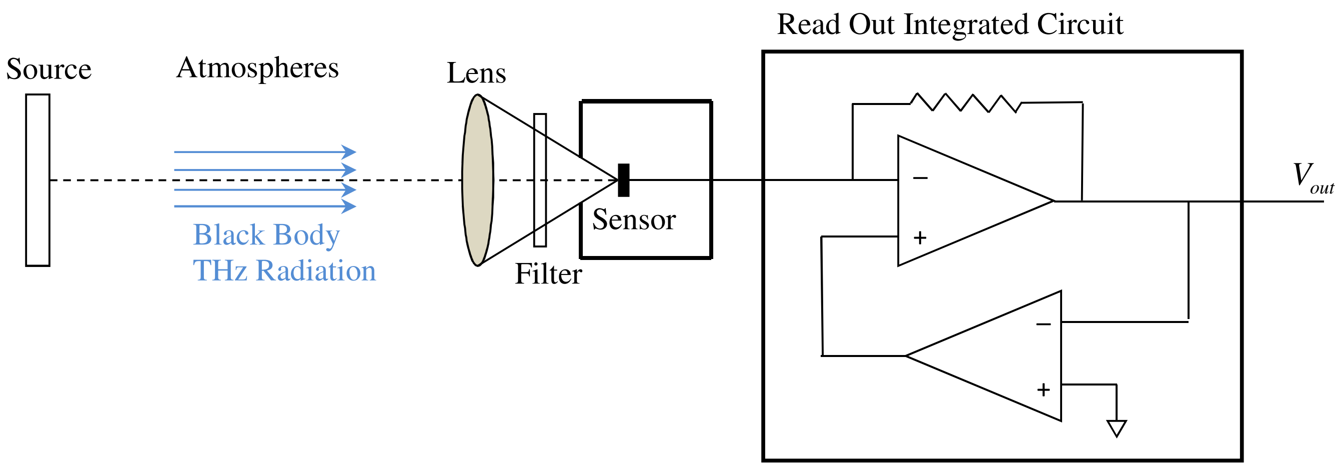
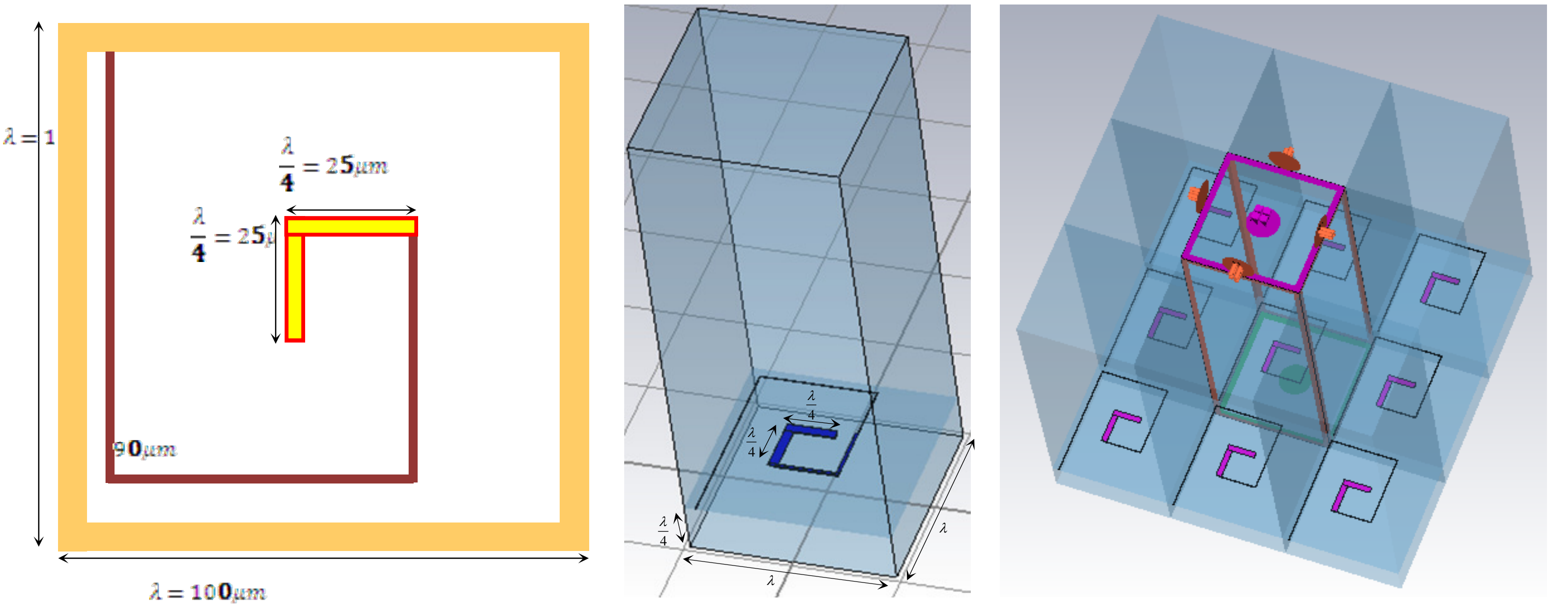


Figure 1 – THz sensor and read out circuit process diagram

4. CST Analysis and Simulation

The CST tool is simulator which performs electromagnetic simulations and computes the s-parameters of the device being simulated. The tool is capable of computing and depicting the electric and magnetic fields created when a 3-dimensional micro structure is radiated with any EM radiation (THz in our case). The calculations are performed according to materials used to build the device thus allowing evaluation of performance when using different materials. In this project, this tool was used to find optimal designs for the geometry of the antenna and the pixels, the size and pitch of the array and the material which would provide the best performance. Learning to use CST effectively was a major challenge as we were the first project team in the VLSI Lab to use the tool for the simulation if a TeraMOS Thermal Antenna.



(a) *(b)* *(c)*

Figure 2- (a) pixel 'Q' with 2 series connected transistor, matched to $\lambda = 100\mu m\ (f = 3THz)$*. (b) Full pixel 'Q' view, pitch is* λ*, antenna matched to* $\lambda/4$ *and optical cavity matched to* $\lambda/4$ *. (c) Periodic array of pixel 'Q'.*

4.1 Antenna Design

The thermal antenna (Fig 2a) has to achieve high absorption (above 90%) in a wide frequency bandwidth. In order to measure the absorption, the s-parameters of the pixel model were calculated by the simulator and extracted in order to measure the efficiency of the antenna. The dependency of the pixel's pitch and the distance between the antenna and the reflector on the main frequency absorbed were carefully analyzed. Simulations were run on many different configurations (pixel geometry, pitch and other geometric parameters) and absorption efficiency for each configuration was measured. Eventually the optimal pitch was found to be $\lambda \times \lambda$, the size (width) of every transistor was set to $\frac{\lambda}{4}$ and the optimal distance between the antenna and the reflector was set to $\frac{\lambda}{4}$ for waveguide impedance matching (Fig 2b). The dependency of the structure size and measurements on the wavelength is due to the required impedance matching of the pixel array operating as a resistive FSS.

4.2 Pixel Array Design and Material Selection

The aim of these simulations was to design a THz pixel array that met the following design requirements:

- Maximum absorption of nearly **100%** (prior results got max 91% absorption)
- **Large bandwidth** around the main frequency
- **Low cost** materials
- **Manufacturable** size and shape of antenna
- **High endurance** (tolerance) to fabrication error
- **Design compatible** to readout circuit
- **High noise tolerance** due to use of SOI technology
- Low cross talk between adjacent pixels

The frequency and amount of absorption depends on the type of the material used to make the absorber. As THz thermal sensors have not been thoroughly studied yet, the most suitable material was unknown. The goal was to find a material with high efficiency and low cost. We created SOI TeraMOS transistors with different resistances for poly and active, and we added metal coating to the transistors.

Three different types of pixels with different sizes and different shapes of antennas matching to different main frequencies were modeled. After a great amount of calculations and simulations the following parameters were found that for all 3 pixels:

- Optimal pixel sizes
- Optimal resistance, width, length of the TeraMOS poly and active
- Optimal material for metal coating (high absorption, producible and considerably low cost) – **Titanium**

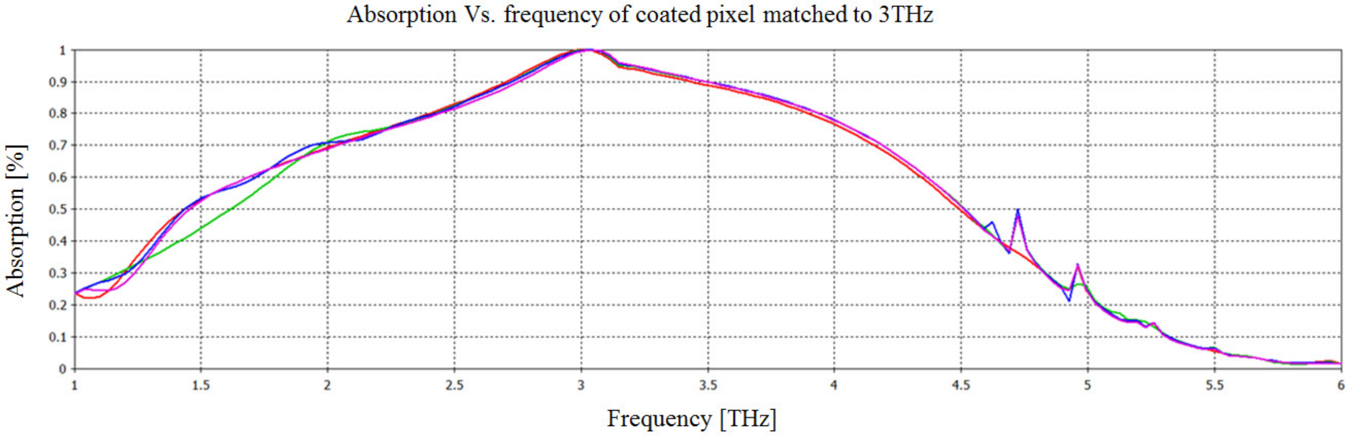


Figure 3 – Diagram of pixel 'Q' with Ti coating matched to 3 THz with 100% absorption and large BW

Using the simulation results, we were able to create a THz thermal pixel array that supported the theoretical calculations, and met the design requirements.

5. Read Out Integrated Circuit (ROIC)

As stated above, the THz radiation impacts the antenna (transistors) of the sensor and changes the current flowing through it. A ROIC is required to sense the current change and covert it to an analog voltage. This voltage reflects the change of temperature in the target which originally emitted the THz radiation.

The THz sensor described above creates a signal in the region of tens to hundreds of picoamperes. It was immediately clear that designing and implementing a ROIC for such a low signal would be beyond the scope of a student project. Therefore, as a part of the ongoing THz research, and as a first step towards designing the TeraMOS ROIC, we were required to analyze, design and implement a single-ended readout integrated circuit with active feedback for a larger signal – in the range of $1-10\,nA$. This readout circuit was to meet the following design requirements:

- Input DC operating point voltage range $0.5 \div 1.5V$
- $Gain \geq 1M\Omega$
- $PM > 60°$
- $BW = 10\,KHz$
- $Power < 0.4[mW]$
- Input referred noise:
    - Thermal noise of $\prec 5\left[\frac{nV}{\sqrt{Hz}}\right]$
    - ${}^{1}\!/_{f}$ noise $\prec 100\left[\frac{nV}{\sqrt{Hz}}\right]\Bigg|_{f=1Hz}$

The main challenge in designing this ROIC is that it requires high gain and low 1/f noise while also requiring phase margin above 60 degrees in the feedback. The readout circuit is based on one voltage operational amplifier and a transadmittance opamp in the feedback. The bias current sets the operation point of the matrix. This matrix is composed from 180 pixels and it is considered as a load. When radiation impacts the sensor, the current changes at the input are amplified and converted to the output voltage.

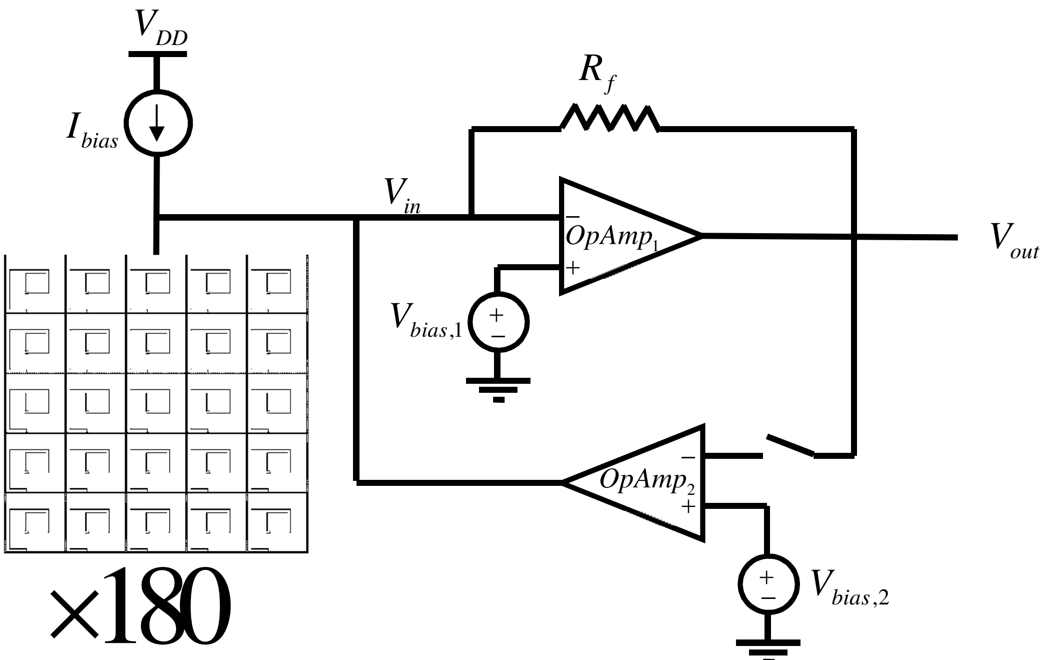
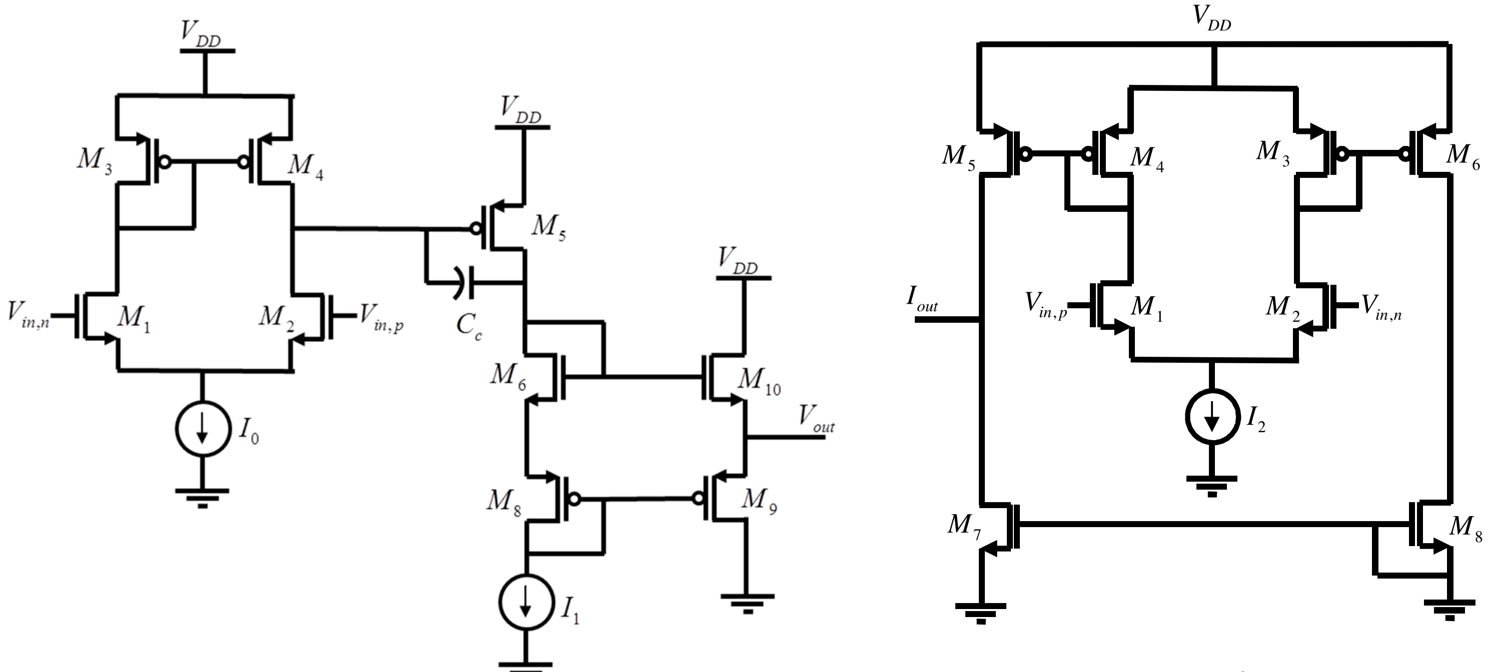


Figure 4- Read out integrated circuit structure

The signal that enters the circuit is very low therefore the read out circuit design needs to have high gain, very low thermal and $\frac{1}{f}$ noise, low power consumption and it needs to be in deep stability. The first opamp (Fig 5a) is built from a differential stage connected to a second stage common source in order to increase the gain, and then connected in series to a push-pull buffer. The buffer separates the opamp from an output capacitance.



(a) *(b)*

Figure 5- (a) Schematics of OpAmp1, 2- stage differential OpAmp with push-pull buffer, (b) Schematics of OpAmp2, transadmitance (TA)

The second opamp (Fig 5b) is a transadmittance amplifier, built from a differential stage and current sources. Its purpose is to perform a calibration once every several seconds, therefore a switch was connected in the feedback. This switch is connected to a clock that operates at a low frequency and activates the calibration process.

The main advantage of this ROIC is that it's adaptively and has the ability to suppress low-frequency noise. The feedback enables the circuit to compensate the low-frequency fluctuations of the current while reading the signal, but at the same time causes stability problems due to the fact that both voltage amplifier and transadmittance amplifier introduce several poles leading to a negative phase margin. In order to overcome this problem, we studied and implemented analog design and stability techniques (for example miller effect, switch in the feedback and more) in order to control the poles' locations and bandwidth of the transfer function of the complete circuit.

The current that is read out from the pixel is very low, therefore the readout circuit needs to have high signal to noise ratio (SNR). A main challenge in the design is to amplify the signal using a large gain, while trying to cancel the 1/f noise and any other low-frequency noise. Our design meets all the above requirements and shows excellent performance.

Summary and Conclusion

In this project we designed an optimal pixel for a thermal sensor based on a THz antenna and using this pixel, we created a full matrix for the sensor. In addition we designed and implemented a compatible ROIC that met the required specifications as the first step towards a THz read out integrated circuit.

The main achievements include:

- Thorough research and implementation of antenna geometry using EM simulations for maximum performance
- Thorough research and implementation of pixel structure, materials and coating, using EM simulations for maximum absorption
- Implementing the pixels as unit cells in the FSS array.
- Thorough research and analog CMOS –SOI integrated circuit, techniques of stability and poles location
- A main challenge in the ROIC design was to amplify a low signal using large gain, while trying to cancel the 1/f and any other low-frequency noise. In addition creating a feedback in deep stability.
- Another one of the main challenges we faced and overcame was to learn, understand and integrate several design disciplines to enable a design of a complete thermal sensor system. These disciplines vary from electromagnetic simulations and optimization of the

device, to analog circuit design and simulations in order to implement a compatible ROIC.

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