Terahertz integrated image detectors

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Outline

- Space applications of THz
- Proposed direct detection architecture
  - 3D antenna for direct injection
  - Rectifying device and charge storage system
- On-wafer measurements
- NEP evaluation
There are several possible applications of a CMOS THz image detector. The main issue is the relatively low cost of the IC, which thus can be used in large number of detector, to be used e.g. for a large area antennas. Sensors can be distribute either in focal plane or out of it, with the possibility to achieve highly resolution images.

There is the additional opportunity to use receivers with antenna tuned at different frequency, and thus obtain “colored” images.

In the terahertz spectra are given the main atmospheric gases ($N_2$, $O_2$, $CO_2$, vapors of $H_2O$ and other gases that participate in metabolic processes in living objects, as well as spectra of some air polluters ($N_2O$, $CO$, $H_2S$, $SO_2$ and others).

Terahertz can be used to monitor dynamic processes in atmosphere,
Ozone depletion,
Distribution of both natural and man-made pollutants,
Water vapour and temperature profiling.

Temperature, pressure, and wind velocity in addition to chemical mixing ratios are all retrievable parameters using narrow band heterodyne radiometry.

Terahertz Waves and Perspectives of Development of Terahertz Biomedical Technologies, V. Betskiyl, et al., Infrared and Millimeter Waves and 13th International Conference on Terahertz Electronics, 2005.
Similar data can be gleaned from the atmospheres of planets, moons, comets and asteroids, including the search for chemical signatures associated with subsurface volcanic activity or even life processes.

Such a wide variety of information can be obtained from these measurements and over objects from distant galaxies to our own.

Already more than half a dozen orbital platforms have been designed and launched with capabilities to record these spectral signatures.

*Terahertz Waves and Perspectives of Development of Terahertz Biomedical Technologies, V. Betskiyl, et al., Infrared and Millimeter Waves and 13th International Conference on Terahertz Electronics, 2005.*
The lack of attenuation in space allows also the design of satellite-to-satellite communication systems with THz carriers.
**Proposed Architecture for Direct Detection**

- **3D tapered conical μ-helix antenna**
- **Ground plane (metallic pad or Si wafer)**
- **Metallic nanometric whisker**
- **Rectifying device and charge accumulation structure hosted in the front-end of a standard CMOS APS wafer**
- **Polymer for mechanical stabilization**
- **TCO for electrical connection to ground for charge extraction path**

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**Primo Workshop Nazionale "La Componentistica Nazionale per lo Spazio: Stato dell’arte, Sviluppi e Prospettive"**
Re-Use of CMOS Pinned Diode Photodetector structure

Noise: 6 el/sec

Primo Workshop Nazionale "La Componentistica Nazionale per lo Spazio: Stato dell’arte, Sviluppi e Prospettive"
The rectifying device is realized within the structure of the standard photo detector.

The antenna is realized on the top of the p-type Si wafer.
Why Direct injection should be better than the MOS rectifiers?

Fig. 1 Detector schematic (a), metal-level antenna geometry (b).
Why direct injection should be better than MOS the rectifiers?

In the direct injection structure the rectifying device is fabricated just below the antenna whisker.
FE factor value as high as 40,000 can be obtained.
Fabrication steps for the micrometric helix antenna.

(a) Antenna pattern
(b) Bond pad pattern
(c) Photoresist deposition
(d) Porous silicon formation in the exposed areas
(e) Metal electroplating
(f) Photoresist removing
(g) Substrate alignment and compression
(h) Pad bonding
(i) Substrates separation and metallic wire release

3D Antenna for Direct Detection
The resonance frequency can be modulated by changing the helix eight
Integrated antennas can also be realized by using directly the metallization of the CMOS IC.
Rectifying device and charge storage system

- First requirement: the integrity of n/p charge storage well must be preserved
- A “metal-p⁺-n⁻” structure is used
On-wafer measurements

- In the first run the antenna was not realized
- A RF pad contacted the whisker and the rectifying structure
Current measurement at 1 G. Hz. TX is always in ON condition.

Equivalent circuit of the measurement setup

Rectified current v. Input power

- On-wafer measurements

- 1 GHz
  - $k = 1.02$

- 40 GHz
  - $k = 0.84$
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\[ P_{RF,N} = -60,61 \text{ dB} @ 1 \text{ GHz} \]

\[ P_{RF,N} = -43,42 \text{ dB} @ 40 \text{ GHz} \]

\[ k = 1,02 @ 1 \text{ GHz} \]

\[ k = 0,84 \text{ dB} @ 40 \text{ GHz} \]

noise level = 32 aA (200 el/sec)
Transient simulations (Synopsis TCAD) show that the decrease of current rectification only occurs at very high frequency, greater than 100 GHz.
NEP evaluation

1 THz

RS–CS model derived by Synopsis TCAD AC analysis
Fig. 2. Transit time $\tau_b$ versus neutral base width, $W$, from scattering matrix approach (SMA) simulation, common approximations, and (1) (which also agrees with the results of [5] and [17]). The SMA results are shown both for simulations with just the emitter and the base (EB) and those also including the collector (EBC).

IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 41, NO. 6, JUNE 1994
A Microscopic Study of Thin Base Silicon Bipolar Tra
Mark A. Stettler and Mark S. Lundstrom
### NEP evaluation

<table>
<thead>
<tr>
<th>Technology</th>
<th>Array size (X*Y)</th>
<th>BW/freq (THz)</th>
<th>(µW/pixel)</th>
<th>max R_y (V/W)</th>
<th>min NEP (pW/Hz^0.5)</th>
<th>frame rate (fps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NbN</td>
<td>64 x 1</td>
<td></td>
<td></td>
<td></td>
<td>0.008</td>
<td>6</td>
</tr>
<tr>
<td>YBCO</td>
<td>1 x 1</td>
<td></td>
<td></td>
<td></td>
<td>20, 1.6THz</td>
<td>-</td>
</tr>
<tr>
<td>HEB</td>
<td>1 x 1</td>
<td></td>
<td></td>
<td>20k, 0.59THz</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>65 nm bulk</td>
<td>32 x 32</td>
<td>0.79-0.96</td>
<td>2.5</td>
<td>115k, 0.86THz;</td>
<td>12, 0.86THz</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>140k, 0.86THz;</td>
<td>100, 0.86THz</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>56.6k, 0.9THz;</td>
<td>470, 0.9THz</td>
<td></td>
</tr>
<tr>
<td>65 nm SOI</td>
<td>3 x 5</td>
<td></td>
<td></td>
<td>1k, 0.65THz</td>
<td>54, 0.65THz</td>
<td>Scan</td>
</tr>
<tr>
<td>65 nm bulk</td>
<td>3 x 5</td>
<td></td>
<td>800, 1THZ</td>
<td>66, 1THZ</td>
<td></td>
<td>Scan</td>
</tr>
<tr>
<td>0.13 µm bulk</td>
<td>4 x 4</td>
<td>0.27-0.29</td>
<td>375</td>
<td>323, 0.28THz</td>
<td>29, 0.28THz</td>
<td>Scan</td>
</tr>
<tr>
<td>(SBD)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.13 µm bulk</td>
<td>3 x 4</td>
<td>0.3-1</td>
<td>97</td>
<td>1.8k, 1.05THz</td>
<td></td>
<td>Scan</td>
</tr>
<tr>
<td>0.15 µm bulk</td>
<td>1 x 1</td>
<td>0.35-0.43</td>
<td>-</td>
<td>11, 4.1THz</td>
<td>1330, 4.1THz</td>
<td>Scan</td>
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<tr>
<td>0.25 µm bulk</td>
<td>3 x 5</td>
<td></td>
<td>5500</td>
<td>80k, 0.6THz</td>
<td>300, 0.6THz</td>
<td>Scan</td>
</tr>
</tbody>
</table>

**Evaluated NEP at 1 THz**

\[
\text{NEP} = 51 \text{ pW/Hz}^{0.5}
\]

**Noise:** 200 el/sec
CONCLUSIONS

- We proposed direct detection architecture for THz
- The architecture is based on the CMOS pinned photodiode
- 3D antenna can strongly improve the detection
- At the moment there is only a low frequency characterization, based on On-Wafer measurements
- We obtained a very promising NEP evaluation