Sensing, Detection and Imaging using Millimeter-wave and THz CMOS ICs

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Outline

• Gas Absorption Spectroscopy
• CMOS Technology Trend
• Schottky Diodes in Silicon
• Spectrometer in CMOS
• 280-GHz Schottky Diode Detector
• Summary
Spectrometer

- Sample chamber, transmitter with a tunable frequency source and a detector.
- Like a radio. Transmits through a chamber and measures the signal strength of received signal.
- Repeat at varying frequencies to determine frequency response. Identify contents of the sample.
Evolution of Gas Analysis

1974 Hewlett-Packard Microwave
- 40 GHz
- 2000 Volts
- 50,000 sec/scan
- $450,000 in 1974

2003 InP (HRL) THz FASSST
- 330 GHz
- 2.5 Volts
- 1 sec/scan
- $?? in 2005
Spectroscopy Overview

- **Sub-millimeter (SMM) Spectroscopy** exploits rotational transitions of gas molecules.

![Graph showing spectral brightness, purity, frequency calibration, and agility.](image)

- Three seconds of data acquisition expands to 1 kilometer at scale of lower panel.

(Courtesy Frank De Lucia, Ohio State University)
Spectroscopy System

- Detects 200 kHz modulation (limited by linewidth)
- Sidebands grow as $24^2 = 576$
- Rejects unwanted mixing products
- Produces fast sweeps and ~100 kHz FM modulation for probe
- Dynamic Range: DC level maintained until detector that demodulates FM
- IF Bandwidth to include sweep width $\delta$ (receiver steps)
- Receiver steps, does not sweep
- Produces steps of 0.25 MHz for both receiver and as input to mixer for transmitter

(Courtesy Frank De Lucia, Ohio State University)
Spectroscopy System

- Power module
- Central computer
- Pumps
- Touch pad and USB interface
- RF electronics
- Gas inlet
- THz Tx/Rx
- Spectroscopic cell
- Sorbent tube
- Vacuum manifold

(Courtesy Frank De Lucia, Ohio State University)
Projected NMOS Transistor Requirements

- Enabled by the scaling of CMOS technology.
- $f_T$ and $f_{\text{max}}$ are 485 and 420 GHz for CMOS transistors in production.

- NMOS transistors with $f_{\text{max}}$ of 600 GHz is projected to be required within three years.
- Schottky diodes with measured cut-off frequency of ~2THz.
Shallow Trench Isolation Separated Schottky Diodes

- Diffusion area without implant forms a Silicide-Si junction. (TiSi$_2$, CoSi$_2$, NiSi$_2$)
- Ohmic contacts on n-well form the n-terminal.
- Requires no process modifications.
- Spreading resistance of a square diode is $\sim R_{sq,n\text{-well}}/29$.
- At given area, the resistance can be lowered by breaking a big square into multiple parallel smaller squares.
- Single cell diode area is 0.32 x 0.32 $\mu$m$^2$ in 130-nm CMOS.

$f_{\text{cutoff}} = \frac{1}{2 \cdot \pi \cdot R_{\text{total}} \cdot C_0}$
• The capacitance increases with smaller proportion, since the area is kept the same.
• Measured $f_{\text{cut-off}}$ to $\sim 1.5$ THz in 130-nm CMOS.
• The cut-off frequency does not scale well with technology.
• The resistance of silicon region surrounded by STI becomes dominant.
• Exacerbated with technology scaling by the fact that STI thickness scales slower and capacitance/area increases.
Polysilicon Gate Separated Schottky Diodes

- Schottky diode area is separated by polysilicon gate on gate oxide layer.
- Eliminates the silicon region surrounded by STI.
- Independent of STI thickness scaling. Should scale better.
- The measured $f_{\text{cut-off}}$ is $\sim 2.0$ THz for a structure fabricated in 130-nm CMOS.
- Ideality factors of diodes for different structures and in different nodes vary between 1.05 to 1.20.
CMOS Approach

• Integration of millimeter wave or sub-millimeter wave circuits with baseband analog and digital subsystems.

• Higher level of integration will lead to smaller size and simplification of high frequency interconnections.

• High yield.

• Digital subsystems and calibration can be used to correct the imperfections for higher yield and better performance.

• Potentially low cost
## Partial EPA list of harmful molecules

<table>
<thead>
<tr>
<th>Gas</th>
<th>Frequency (MHz)</th>
<th>Fatality Limit</th>
<th>Gas</th>
<th>Frequency (MHz)</th>
<th>Fatality Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen Cyanide (HCN)</td>
<td>265887.1094</td>
<td>15-50 ppm/hr</td>
<td>Methyl Bromide (CH₃Br)</td>
<td>267801.2188</td>
<td></td>
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<tr>
<td>Cyanogen Chloride (CICN)</td>
<td>267199.53125</td>
<td></td>
<td>Ethylene Oxide (C₂H₄O)</td>
<td>263292.5156</td>
<td>200 ppm/hr</td>
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<tr>
<td>Cyanogen Bromide (BrCN)</td>
<td>263578.3438</td>
<td></td>
<td>Acrolein (C₃H₄O)</td>
<td>267279.3594</td>
<td>1.4 ppm/hr</td>
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<tr>
<td>Acetonitrile (CH₃CN)</td>
<td>239096.6719</td>
<td></td>
<td>Propionitrile (C₂H₅CN)</td>
<td>268829.0625</td>
<td></td>
</tr>
<tr>
<td>Carbonyl Sulfide (OCS)</td>
<td>267530.4219</td>
<td></td>
<td>Vinyl Chloride (C₂H₃Cl)</td>
<td>266151.2969</td>
<td></td>
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<tr>
<td>Methyl Chloride (CH₃Cl)</td>
<td>265785.4219</td>
<td></td>
<td>Methyl mercaptan (CH₃SH)</td>
<td>227564.6719</td>
<td>23 ppm/hr</td>
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<tr>
<td>Acrylonitrile (C₂H₃CN)</td>
<td>265935.2031</td>
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<td>Methyl isocyanate (CH₃NCO)</td>
<td>269788.6094</td>
<td>5 ppm/hr</td>
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<tr>
<td>Dichloromethane (CH₂Cl₂)</td>
<td>259215.3906</td>
<td></td>
<td>Methanol (CH₃OH)</td>
<td>250507.1563</td>
<td></td>
</tr>
<tr>
<td>Methyl Iodide (CH₃I)</td>
<td>269864.9063</td>
<td></td>
<td>Formaldehyde</td>
<td>211211</td>
<td>100 ppb</td>
</tr>
</tbody>
</table>

**CO (230538), Ethanol (246663.6), Acetone (259618.4), NO (267199.53125)**
Medical Monitoring

Improved predictive models for plasma glucose estimation from multi-linear regression analysis of exhaled volatile organic compounds

- Some 3000 different molecules have been detected.

- Breath analyses is a blood test.

- Spectrometer for blood sugar level detection for diabetic patients (ethanol, acetone, methyl nitrate, ethylbenzen).

- Lung cancer detection.

- Current technique: gas chromatography mass spectrometry.
180-300 GHz Spectrometer

- Rotational spectroscopy.
- Specificity in the presence a large number type of molecules in a mixture.
- Detect down to Parts Per Trillion (PPT).
- Use water line (183 GHz) for calibration.

F. Patten, MACS Proposer Day Conf., Darpa, Nov. 2005
Millimeter-wave & Sub Millimeter-wave Spectroscopy

- Transmits and measures the received signal amplitude.
- Absorption cell needs to be pumped to ~ 0.1-1 mT. Size can be reduced to 10’s of cm.
- Multiple TX-RX pairs
  - alleviates the tuning range problem.
  - Reduces the required bandwidth of antennas
  - Simultaneous scan (faster).
Fractional-N Synthesizer with wide bandwidth for:
- fast settling time
- frequency step of ~10kHz (0.003 ppm).

Output power ~10-100 μW.
- 99% of power should reside within +/- 100 kHz.
- Output frequency range from 180 to 300 GHz (20 GHz band each).

45-nm CMOS Technology.
Receiver Architecture

• Direct Conversion
  - RF at 180-300 GHz, IF at 10-20 MHz
  - Single harmonic passive mixer
  - Large LO swing required at a higher frequency

• Heterodyne
  - RF at 180-300 GHz, IF$_1$ at 100 GHz
  - One passive mixer at RF and one active at IF$_1$
  - Large LO swing required at a smaller frequency
Receiver Architecture: Direct Conversion

- Low IF (~ 10-20MHz) architecture
  - Single-step down conversion
  - High LO frequency required
    - Small swing
    - Large phase noise
## Receiver Architecture: Direct Conversion

- System simulation results for
  - Input RF power = -40 dBm
  - LO power = 0 dBm
  - IF frequency = 15 MHz
  - APDP SHM mixer

  conversion loss = 18 dB

<table>
<thead>
<tr>
<th>Test points</th>
<th>Mixer in (RF) port</th>
<th>Mixer out port</th>
<th>Filter out port</th>
<th>IF out port</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (dBm)</td>
<td>-50</td>
<td>-68.2</td>
<td>-69.9</td>
<td>-44.9</td>
</tr>
<tr>
<td>Gain (dB)</td>
<td>0</td>
<td>-18.2</td>
<td>-19.9</td>
<td>5.8</td>
</tr>
<tr>
<td>Noise Figure (dB)</td>
<td>0</td>
<td>18.4</td>
<td>18.6</td>
<td>23.1</td>
</tr>
</tbody>
</table>
Receiver Architecture: Heterodyne

- Low IF (~15 MHz) architecture
  - Two-step down conversion
    - Low LO frequency required
      - Large swing
      - Better phase noise
  - Circuit complexity and area increases
Receiver Architecture: Heterodyne

- System results for 180-200GHz band
  - Input RF power = -50 dBm and LO power = 5 dBm
  - IF frequency = 10 MHz
  - APDP SHM conversion loss = 18 dB

<table>
<thead>
<tr>
<th>Test points</th>
<th>Mixer1 in (RF) port</th>
<th>Mixer1 out port</th>
<th>Filt1 out port</th>
<th>Mixer2 in port</th>
<th>Mixer2 out port</th>
<th>Filt2 out port</th>
<th>IF out port</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (dBm)</td>
<td>-50</td>
<td>-68.1</td>
<td>-69.2</td>
<td>-57.1</td>
<td>-55.2</td>
<td>-57.0</td>
<td>-32.0</td>
</tr>
<tr>
<td>Gain (dB)</td>
<td>0</td>
<td>-18.1</td>
<td>-19.2</td>
<td>-7.1</td>
<td>-5.2</td>
<td>-7.0</td>
<td>17.8</td>
</tr>
<tr>
<td>Noise Figure (dB)</td>
<td>0</td>
<td>18.2</td>
<td>18.7</td>
<td>22.7</td>
<td>26.2</td>
<td>26.3</td>
<td>26.4</td>
</tr>
</tbody>
</table>
Sub-harmonic Mixer (SHM)

- Difficult to generate fundamental frequency LO signal at sub-millimeter wavelengths with sufficient power and low phase noise.
- SHM uses $n^{th}$ harmonic of the LO signal for its conversion products.
  - RF is mixed with the second harmonic ($n=2$) of the generated LO signal.
Anti Parallel Diode Pair (APDP)

- n-type SBDs have higher electron mobility
  - Parasitics hurt at mm-wave frequencies
- cutoff frequencies
  - \(\sim 1\) THz for c-APDP
    (130nm CMOS process)
APDP Mixer Versions

- APDP (SBD pair in shunt configuration) mixer.
- Modified Wilkinson Power Combiner
APDP Mixer Measurement

- Chip die photo and test setup

Die microphotograph

Test setup
Simulation Results for 220 GHz-240 GHz

- $RF_{\text{freq}} = 220$-240 GHz
- $LO_{\text{freq}} = 56$-66 GHz
- $IF_{\text{freq}} = 108$ GHz
- $P_{RF} = -40$ dBm and $P_{LO} = 0$ dBm
- $S_{22}$ and $S_{33} < -10$ dB
- $G_c \approx -6$ dB
Simulation Results for 240 GHz-260 GHz

- $RF_{freq} = 240-260$ GHz
- $LO_{freq} = 66-76$ GHz
- $IF_{freq} = 108$ GHz
- $P_{RF} = -40$ dBm and $P_{LO} = 0$ dBm
- $S_{22}$ and $S_{33} < -10$ dB
- $G_c \approx -5$ dB
Simulation Results for 260 GHz-280 GHz

- $\text{RF}_{\text{freq}} = 260$-280 GHz
- $\text{LO}_{\text{freq}} = 76$-86 GHz
- $\text{IF}_{\text{freq}} = 108$ GHz
- $P_{\text{RF}} = -40 \text{ dBm}$ and $P_{\text{LO}} = 0 \text{ dBm}$
- $S_{22}$ and $S_{33} < -10 \text{ dB}$
- $G_c \approx -4 \text{ dB}$
Simulation Results for 280 GHz-300 GHz

- $RF_{freq} = 280$-300 GHz
- $LO_{freq} = 86$-96 GHz
- $IF_{freq} = 108$ GHz
- $P_{RF} = -40$ dBm and $P_{LO} = 0$ dBm
- $S_{22}$ and $S_{33} < -10$ dB
- $G_c \approx -4$ dB
Spectrometer Summary

• Link budget and system analysis for gas absorption spectroscopy
• First reported sub-THz (200 GHz) mixer in a standard CMOS process
  - APDP passive mixer with ~ 26 dB loss
• Future work:
  - Improved Diode Mixers and Active Mixers
  - Baseband blocks
    • Very low noise IF amplifier
    • Band pass filter
• Design of the complete receiver completed in 65nm CMOS.
  - Testing of complete integrated receiver
280-GHz Schottky Diode Detector

- Integrates on-chip patch antennas
- Integrates differential amplifier following the PGS Schottky diode detector
- 2x2 Array
- 130-nm CMOS


Courtesy: K. K. O (UT Dallas)
Measurement Set-up

- Source: frequency sextupler cascaded with a tripler
- Modulation frequency: up to 10 MHz
Responsivity versus Frequency

- Peak responsivity (80kV/W, 50dB amplifier gain included) occurs at 280.6-GHz radiation frequency
- The responsivity without amplifier is 250V/W
- Measurement and simulation matches well, and give the same optimum bias point.
Noise Equivalent Power

- The flicker noise corner frequency of the diode is 4 MHz. At 1 MHz, the noise voltage is $4.1 \text{nV/Hz}^{0.5}$.
- NEP at 1 MHz for single diode detector is $32\text{pW/Hz}^{0.5}$. At 4 MHz, it should be able to get $16 \text{pW/Hz}^{0.5}$.
- The amplifier bandwidth is around 2 MHz.
## 280-GHz Detector (Measurement Summary)

Time Domain Output (distance=38 cm)

<table>
<thead>
<tr>
<th>RF Frequency</th>
<th>Source Mod. Frequency</th>
<th>Source Power at 280GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>280.6 GHz</td>
<td>1 MHz</td>
<td>~25mW</td>
</tr>
</tbody>
</table>

**Responsivity**

- **Bias Current**
  - 40 µA/detector
  - P-P Output at 20mm distance: ~70 mV

**Simulated Antenna Efficiency**

- **Simulated Antenna Gain**
  - ~-1dBi
  - On-chip amplifier gain: ~50 dB

**Noise Floor at 1 MHz (four cell)**

- Noise Equivalent Power at 1 MHz (each cell)
  - NEP at Mod freq. = 4 MHz, 4.1 nV/sqrt(Hz), Best among diode detectors.
  - 16pW/sqrt(Hz) (Projection)
- 290-GHz transmitted power from the source is 4mW and modulation frequency of 250Hz.
- Should work with less than 1µW with better designed.
280-GHz Schottky Diode Detector

• Diode cut-off frequency is ~2 THz. A 1-THz detector should be possible.
Summary

• Schottky barrier diodes with cut-off frequency > 2 THz demonstrated in CMOS technology

• Integrated CMOS transceiver using Schottky barrier diodes for 180-300 GHz spectroscopy under investigation
  - uses Anti-parallel diode-pair (APDP) based sub-harmonic mixer front-end

• 280 GHz detector using Schottky barrier diodes for active imaging demonstrated in CMOS
Acknowledgement

• Collaborators: Kenneth K. O, Rashaunda Henderson, Andrew Blanchard (UTD)

• Students: M. F. Hanif, R. Uddin, Shanthi B., R. Kini, S.-R. Ryu

• The efforts were supported by
  • SRC
  • TxACE at UT Dallas
  • C2S2

• The authors also thank TI for fabrication support.