CMOS THz Detectors for Imaging

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Outline

I. Introduction and Background
II. Detector Implementation
III. Detector Characterization
IV. THz Transmission Imaging
V. Summary
I. Introduction and Background

• **THz radiation:**
  – THz band: 300GHz – 3THz, $\lambda_0 = 1\text{mm} - 100\mu\text{m}$
  – Unique physical properties
  – Applications
    • Non-destructive testing/ quality control
    • Security imaging
    • Wireless communications
I. Introduction and Background

• FETs as THz detectors
  – Rectification of THz radiation
    • Radiation coupling: antenna or grating
    • Theories: Dyakonov-Shur plasma wave theory; distributed resistive self-mixing

\[ V_{gs} \]: gate bias
\[ U_a \]: irradiation induced ac voltage
\[ \Delta U \]: photoresponse

THz, modulated

\[ \Delta U : f_{mod} \]
I. Introduction and Background

• Si CMOS THz detectors
  – First demonstration in 2004, Knap group
  – Focal plane arrays in 2008, Pfeiffer & Roskos groups
  – This work: single detectors and arrays for 0.3-1.05 THz

II. Detector Implementation

• Test chip micrograph

- 0.13µm CMOS
- Bulk Si substrate
- 210µm pixel pitch
- Pixel variants
  - FET, antenna
  - amplifiers
- 3x4 pixel imager prototype: amps + multiplexing
II. Detector Implementation

- Pixel architecture

- Bow tie antenna in metal back end
- Rectifying nMOSFET, variations:
  - $L=130\text{nm} - 300\text{nm}$,
  - $W=250\text{nm} - 10\mu\text{m}$
- Optional: in pixel baseband amplifier, $G=31\text{dB}$
II. Detector Implementation

- Amplifier schematic

- pMOSFETs
- MIM capacitor for feedback
- $G=31\text{dB}$, $2\text{MHz}$ BW
- Low consumption $97\mu\text{W}@1.2\text{V}$
- Low input noise: $16\text{nV}/\text{Hz}^{0.5}@30\text{kHz}$
II. Detector Implementation

• Pixel micrograph
II. Detector Implementation

- 3x4 pixel imager with multiplexing

Pixel multiplexing with:
- 2 shift registers
- 2 clock, 2 reset signals
II. Detector Implementation

- Pixel multiplexing
  - Shift register with D-flip-flops
III. Detector Characterization

• Set-up

![Diagram of detector setup]

- THz Source
- Chopper
- Parabolic Mirror
- Plane Mirror
- Test Chip on Translation Stage
- Lock-In
- Ref.
- Vout
- X, Y
III. Detector Characterization

• Set-up

THz Source
Parabolic Mirrors
Chopper
Translation Stage
Imager

III. Detector Characterization

• Set-up: beam power measurement
  – THz power meter, *Thomas Keating*
  – Large aperture: 3 x 4cm
III. Detector Characterization

- Results 1/5: pixels without amplifier
  Raster scan image of source beam at 300GHz

\[ V_{gs} = 0.1 \text{V} \]
\[ P_{beam} = 2 \text{mW} \]

\[ \Delta U_{\text{max}} = 19 \text{mV} \]

\[ R_v = \frac{\int \int \Delta U \, dx \, dy}{P_{\text{beam}} \cdot A_{\text{det}}} \]

\[ A_{\text{det}} = (\text{pixel pitch})^2 \]
III. Detector Characterization

- Results 2/5: pixels without amplifier
  Responsivity & NEP at 300GHz

\[ NEP = \sqrt{4kT R_{ds}} / R_v \]

\[ NEP_{\text{min}} = 8 \text{ pW/Hz}^{0.5} \]
III. Detector Characterization

- Results 3/5: pixel C14 without amplifier
  Responsivity from 270-1050 GHz

\[ R_{v,\text{max}} = 5 \text{kV/W} \]
III. Detector Characterization

• Results 4/5: pixel with amplifier,
  Raster scan image of source beam at 300GHz

\[ V_{gs} = 0.1 \text{V} \]

\[ P_{beam} = 0.8 \text{mW} \]

\[ V_{out,\text{max}} = 165 \text{mV} \]
III. Detector Characterization

- Results 5/5: pixel with amplifier. Detector signal & responsivity at 300GHz

\[ R_{v,max} = 90 \text{ kV/W} \]
IV. THz Imaging

- **Transmission** imaging of objects
IV. THz Imaging, 300GHz

- chocolate with metal object inside
  → application: food control
IV. THz Imaging, 300GHz

- tree leaves → agriculture: water saving

![Leaf Images](image1)

![THz Image](image2)

225x600 scanned points
V. Summary

- Demonstration of sensitive THz detectors & 3x4 pixel array in CMOS
  - nMOSFET THz detectors
  - Integrated broad band bow tie antennas
  - Pixel consumption <100µW
  - High responsivities: 90kV/W @300GHz, 1.8kV/W @1.05THz
  - Low NEP: <10pW/Hz^{0.5} @300GHz
  - High quality THz images @300GHz
Recent Publications


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Questions?