Demonstration of Tunable Antenna-Coupled Intersubband Terahertz (TACIT) Mixer

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Motivation

Sensitive THz mixer for 2-5 THz that works at relatively high temperature (50-70 K)
- high-resolution THz spectroscopy in deep space, etc

Superconducting hot-electron bolometer

- $T_N \sim 10^*$ quantum limit
- IF Bandwidth $\sim 3$ GHz
- LO power $\sim 1 \mu W$
- Works below 4 K

Schottky diode

- Works at ambient $T$
  - $T_N \sim 50^*$ quantum limit
  - LO power $\sim 1$ mW

TACIT

- $T_N \sim 10^*$ quantum limit
- LO power $\sim 1 \mu W$
- Works at 50-70 K
- IF bandwidth $> 6$ GHz
- Tunability!

Demonstrated 😊

Giovine et al, MICROELECTRONIC ENGINEERING, 88, 2544-2546. (2011)
Hot-electron Bolometer Based on High-mobility 2DEG in GaAs/AlGaAs QW

Two-terminal Hot-electron Bolometer (HEB) based on high-mobility 2DEG:

Mixing demonstrated at ~ 100 GHz with wide IF bandwidths:
- ~ 3 GHz for phonon-cooled device\(^1\) @ 77 K
- ~ 20 GHz for diffusion-cooled device\(^2,3\) @ 77 K
- ~ 40 GHz for ballistically cooled device\(^4\) @ 1.5 K

But, due to large kinetic inductance, RF coupling efficiency significantly degrades above ~500 GHz.

\(^1\) Ynvesson, Appl. Phys. Lett. 76, 777 (2000)
\(^3\) D. V. Morozov et al, Semiconductors 39, 1082 (2005)
\(^4\) M. Lee et al, Appl. Phys. Lett. 78, 2999 (2001)
There’s another way of absorbing THz radiation!

Intersubband transitions\(^1\):

This requires THz E-fields oriented perpendicular to 2DEG plane:

No photocurrent generated!

1 wide (~40 nm) QW

\(^1\) Figure from A. Vasanelli et al. C. R. Physique 17, 861-873 (2016)

Independent tuning of \(n_s\) and \(E_{DC}\) is possible:

\[
\begin{align*}
n_s & \propto (V_T + V_B) \\
E_{DC} & \propto (V_T - V_B)
\end{align*}
\]
Two Advantages

\( n_s \) tunes RF impedance:

\[ R_{zz} \propto n_s \]

\( E_{DC} \) tunes detection frequency:

\[ J. B. Williams et al, PRL, 87, 3 (2001) \]
**Fabricated Prototype Device**

**Vertical Profile:**
- Top gate
- Si substrate
- Back gate
- Source
- Drain
- d~660 nm

**QW structure:**
- 1 QW
- 40 nm GaAs
- $n_s \sim 2 \times 10^{11}$ cm$^{-2}$
- $\mu \sim 10^7$ cm$^2$/V-s at 2 K

**Near active region:**
- Slot antenna (buried)
- Front gate (active region)
- 2DEG mesa

**Top-down View:**
- 2DEG Mesa
- To source
- To drain
- To top gate
- To back gate

**Side View:**
- THz E field

**Grown in MBE @ Princeton**
Bolometric Response at 50 K

To source

To drain

$V_T = 0 \text{ V}$

$V_B = 0 \text{ V}$

Gate works!
Direct Detection at 36 K

Quasi-optical coupling:

0.0
0.2
0.4
VT ㅡ VB (V)
Responsivity at 2.52 THz (a.u.)
VT + VB = -0.75 V

0.0
0.4
0.8
1.2
1.6
2.0
2.5
3.0
3.5
4.0
Effective DC Electric Field (mV/nm)
Absorption Frequency (THz)

10% bandpass filter

TACIT mixer
Si lens
LHe dewar
LNA
Bias-T

RT amp.

Power meter

Mixer dc bias

FIR gas laser

Grid attenuator

Beamsplitter

Model

Absorption Frequency (THz)

2.52 THz

V_T – V_B (V)

2.52 THz

3.11 THz

V_T + V_B = -0.75 V

1e10 cm^-2

3.11 THz

2.52 THz
Direct Detection at 36 K

**Quasi-optical coupling:**

![Diagram of quasi-optical coupling](image)

- **Model:**
  - LHe dewar
  - Bias-T
  - LNA
  - TACIT mixer
  - Si lens
  - 10% bandpass filter
  - RT amp.
  - Mixer dc bias
  - Bandpass filter
  - Power meter
  - FIR gas laser
  - Grid attenuator
  - Beamsplitter

- **Absorption Frequency (THz):**
  - 2.52 THz
  - 3.11 THz

- **Responsivity at 2.52 THz (a.u.):**
  - $V_T - V_B = -0.75$ V
  - $V_T - V_B = -0.50$ V

- **Responsivity at 3.11 THz (a.u.):**
  - $V_T + V_B = -0.75$ V
  - $V_T + V_B = -0.50$ V

**Graphs:***

- **Effective DC Electric Field (mV/nm):**
  - 1e10 cm$^{-2}$
  - 1.2e11 cm$^{-2}$

- **Absorption Frequency (THz) vs. Effective DC Electric Field (mV/nm):**
  - 2.52 THz
  - 3.11 THz
Direct Detection at 36 K

Quasi-optical coupling:

TACIT mixer

Si lens

LHe dewar

LNA

Bias-T

RT amp.

Bandpass filter

Mixer dc bias

FIR gas laser

Grid attenuator

Beamsplitter

10% bandpass filter

Model

Absorption Frequency (THz)

FIR gas laser

Absorption Frequency (THz)

Responsivity at 2.52 THz (a. u.)

Responsivity at 3.11 THz (a. u.)

Effective DC Electric Field (mV/nm)

Absorption Frequency (THz)

Responsivity at 2.52 THz (a. u.)

Responsivity at 3.11 THz (a. u.)

-4 -2 0 2 4
0.0
0.2
0.4
VT - VB (V)

VT+VB = -0.75 V

VT+VB = -0.50 V

VT+VB = -0.25 V

-4 -2 0 2 4
0.0
0.4
0.8
1.2
1.6

VT+VB = -0.75 V

VT+VB = -0.50 V

VT+VB = -0.25 V

Absorption Frequency (THz)

1e10 cm⁻²

2.4e11 cm⁻²

1.2e11 cm⁻²

Absorption Frequency (THz)

3.11 THz

2.52 THz

2.4e11 cm⁻²

1.2e11 cm⁻²

3.11 THz

2.52 THz
Heterodyne Detection at 60 K (2.52 THz)

-12dB/octave roll-off due to high-order filtering in IF circuit
Summary and Outlook

Prototype TACIT mixer
- tunability
- THz mixing at 60 K
- IF bandwidth > 6 GHz

Outlook
- Response beyond 3.11 THz (QCL?)
- Noise temperature measurement
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Antenna Design and THz measurements @ JPL

Dr. Jonathan Kawamura
Dr. Boris Karasik

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Prototype TACIT Mixer

Sample structure:

- Si
- 40 nm GaAs
- AlGaAs
- Etch Stop Layer
- GaAs substrate (Semi-insulating)

Grown in MBE @ Princeton

1 QW
40 nm GaAs
\(\mu \sim 10^7 \text{ cm}^2/\text{V-s at 2 K}\)
\(n_s \sim 2 \times 10^{11} \text{ cm}^{-2}\)

Prototype Design:

Top-down View:

Side View:

THz E field
We use a modified version of Epoxy-Bond-And-Stop-Etch (EBASE) flip-chip process\(^1\):

![Diagram of 2DEG Mesa]

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\(^1\)Weckwerth et al. *Superlattices and Microstructures*, 20, 4 (1996)
Fabrication

- Backside removal and gate metallization
- 2DEG Back gate metallization (buried)
- Front gate metallization on SiO$_2$
- Slot antenna (buried)

Fabrication steps:
- Flip-chip bonding and underfilling
- Top gate (with RF choke)
- Underfill epoxy
- 660 nm
- Backside bonding and gate metallization
Bolometric Response at 50 K

- No electrons!
  - Electrons are all depleted and no current flows in the source-drain channel

Source-Drain Voltage (V)
Source-Drain Current (μA)

$V_T = -1 \text{ V}$
$V_B = 0 \text{ V}$
Bolometric Response at 50 K

There are some electrons in the active region that become hot.