SAND2007-3250P

THz Technology and Plasmonic Detectors

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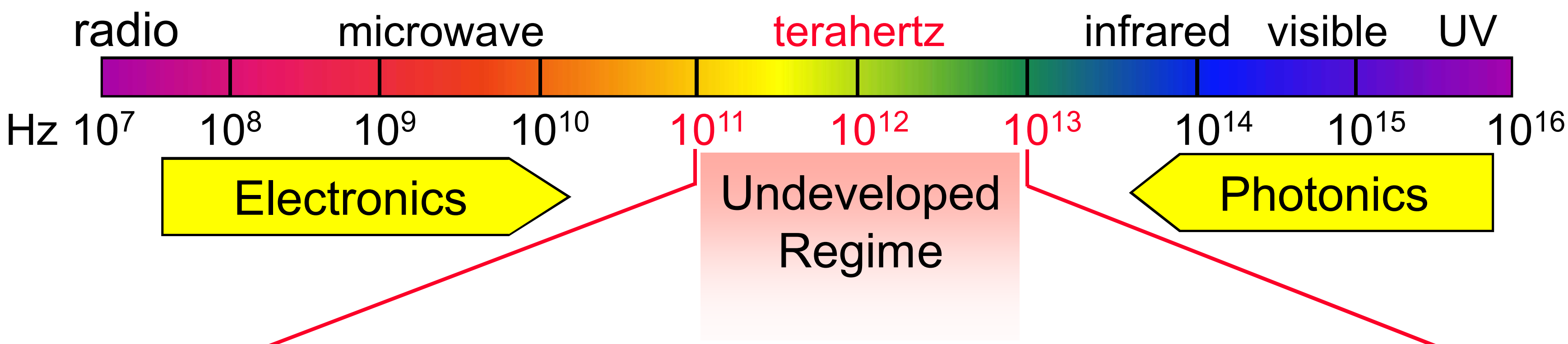
Outline

- **Terahertz intro and motivation**
- THz Sources
- THz Detectors
- Plasmon FET THz detectors
- Conclusion

The THz Spectrum

The Electromagnetic Frequency Spectrum



- **Frequency range 10^{11} to 10^{13} Hz**
  - Wavelength range 3 mm to 30 μm
  - Wavenumber range 3.3 to 333 cm^{-1}
  - Photon energy range 0.4 to 40 meV

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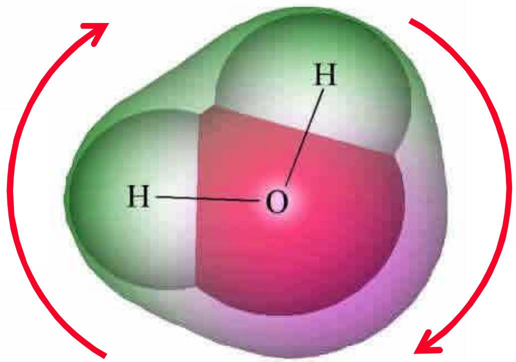
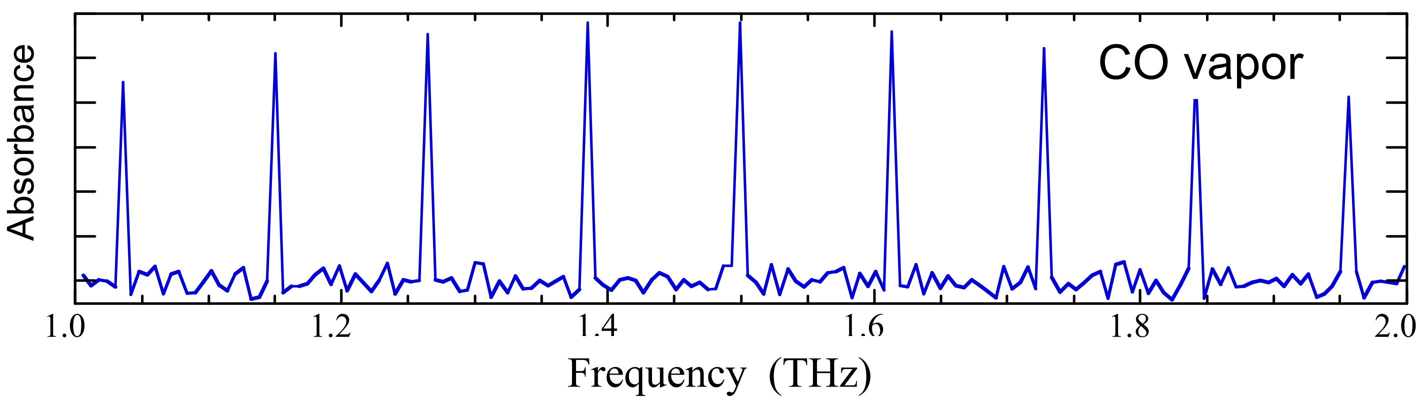
THz Molecular Signatures



- **Rotational resonances in the THz**
- **<u>Moment-of-Inertia spectroscopy</u>:**
  - Depends on *mass distribution*
  - Many distinctive spectral lines

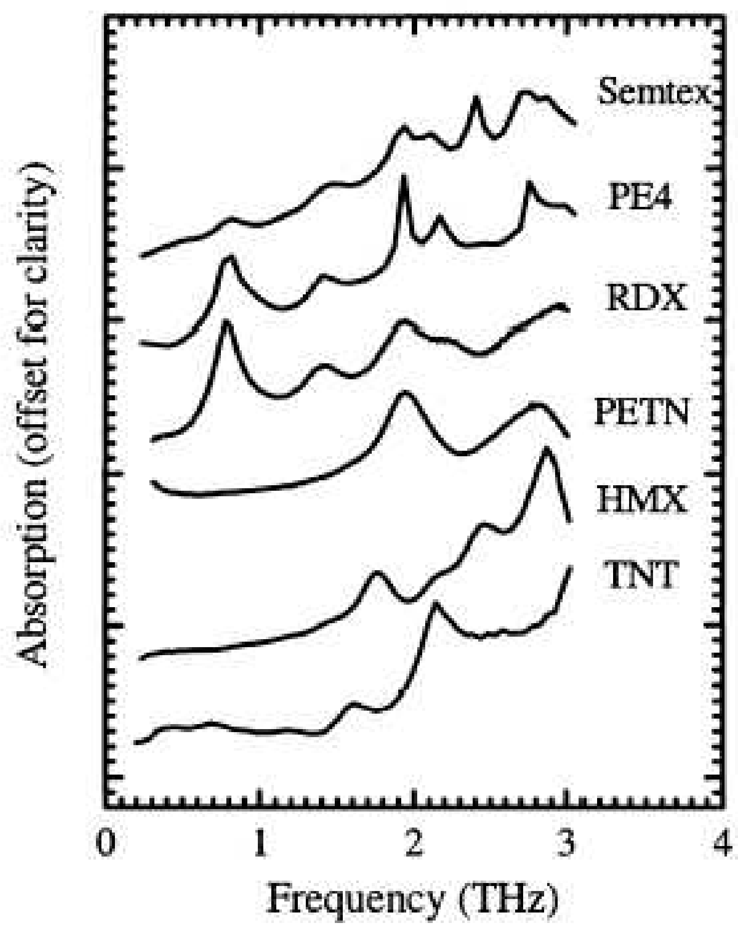
- ***Better chem detection & ID than using other spectral regions***



M. Lee
SNL 01123

...But often requires very high resolution

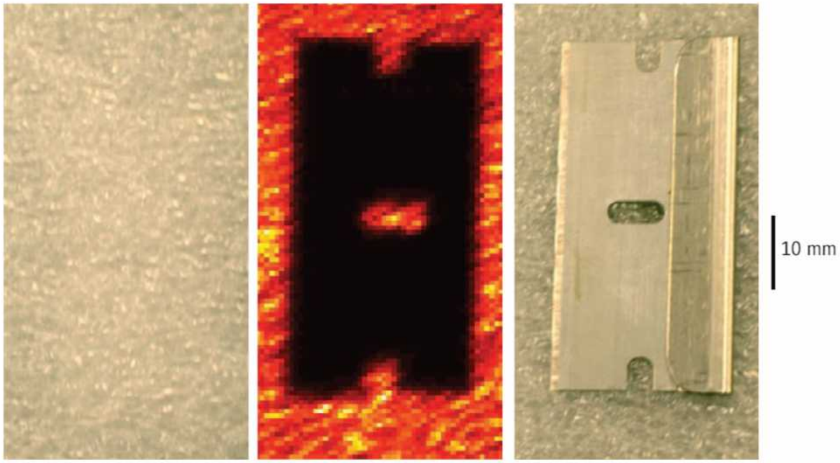
Chemical Identification and THz "See-through" Imaging



Kemp et al. Proc of SPIE **5070**, 2003

0.6 THz image

(from X. C. Zhang, RPI)



Front of thick packing foam | "See-through" image as seen using a 2.9-THz QCL | The real image in the back of the packing foam

M.C. Wanke & I. Brener
Sandia

Secure Wireless Telecomm

Commerical wireless cell phones (3G CDMA):

- Carrier frequency ≈ 2 GHz
- Data rate ~ 3 MB/s max
- Transmission range ~ 1 km
- Dynamic range 140 dB max

Using a THz carrier offers advantages…

Over microwaves:

- Higher carrier ⇒ higher data rates (~10 GB/s)
- Shorter wavelength ⇒ higher directionality
- Secure short burst beamed messages

Over infrared:

- Less scattering by “dry” aerosols (smoke) ?
- Atmospherically limited range < 100 m ⇒ less susceptible to intercept

THz: Other uses

- **Measure Semiconductor properties**
  - **non-contact resistivity**
- **Pharmaceutical Quality control**
  - **Does the pill have anything in it?**
- **Medical Imaging (tumors)**
  - **Non-ionizing radiation**
- **Semiconductor Physics**
  - **frequencies comparable to inverse relaxation times**
  - **plasmons**

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THz Sources: Free Electron Laser

coherent radiation from 120 GHz to 4.5 THz.

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THz Sources: Far-Infrared Laser

CO_2 Laser 10µm wavelength

→

User filled tube (Formic Acid, Methanol)

→

Up to 150mW
Output power

Tunable through choice of gases and pump lines,
Not continuously tunable

THz Sources: Backward Wave Oscillator

Conventional

New Development

TeraPhysics

Claim 40mW tunable THz output

600 times smaller than conventional unit

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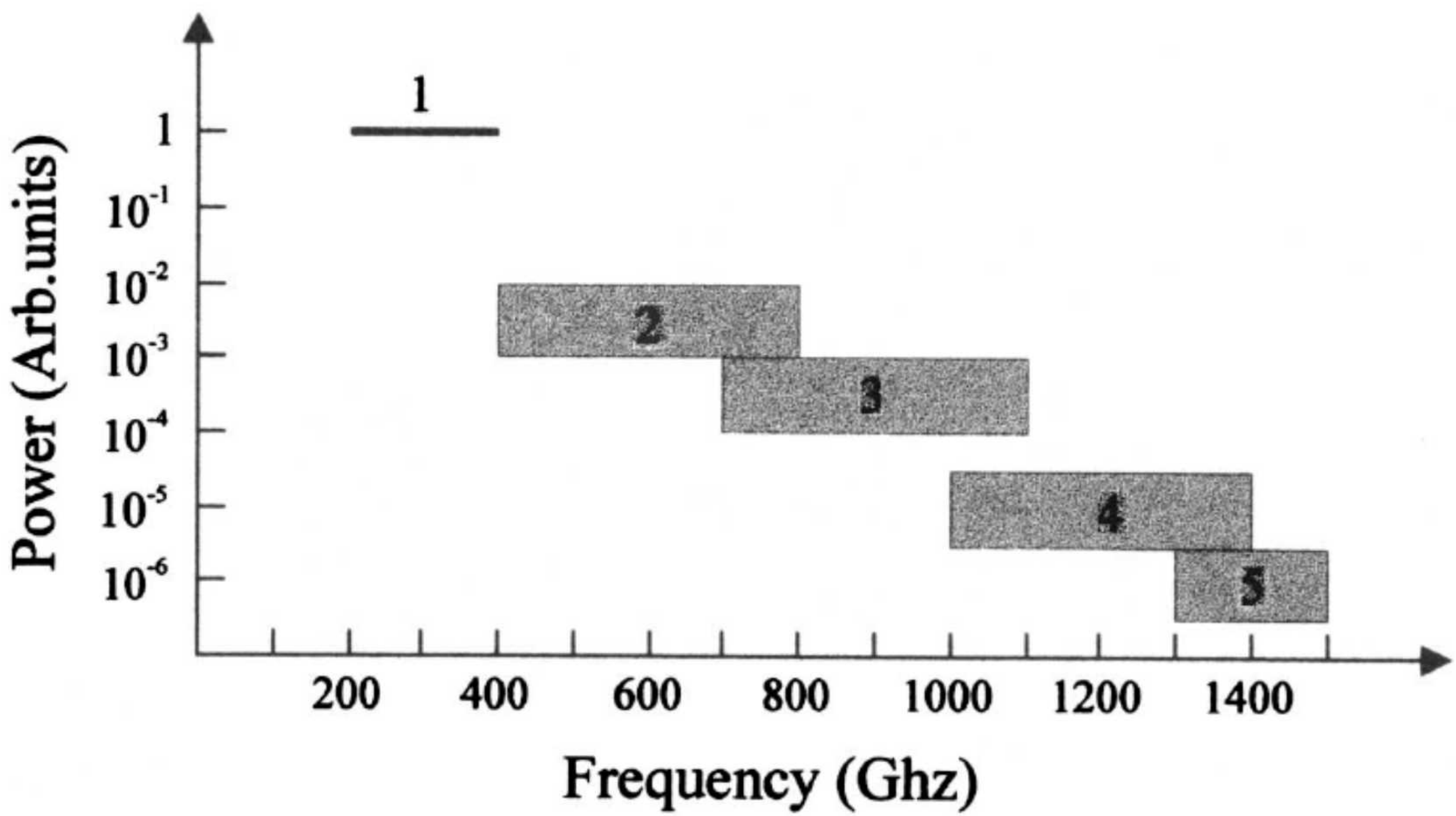
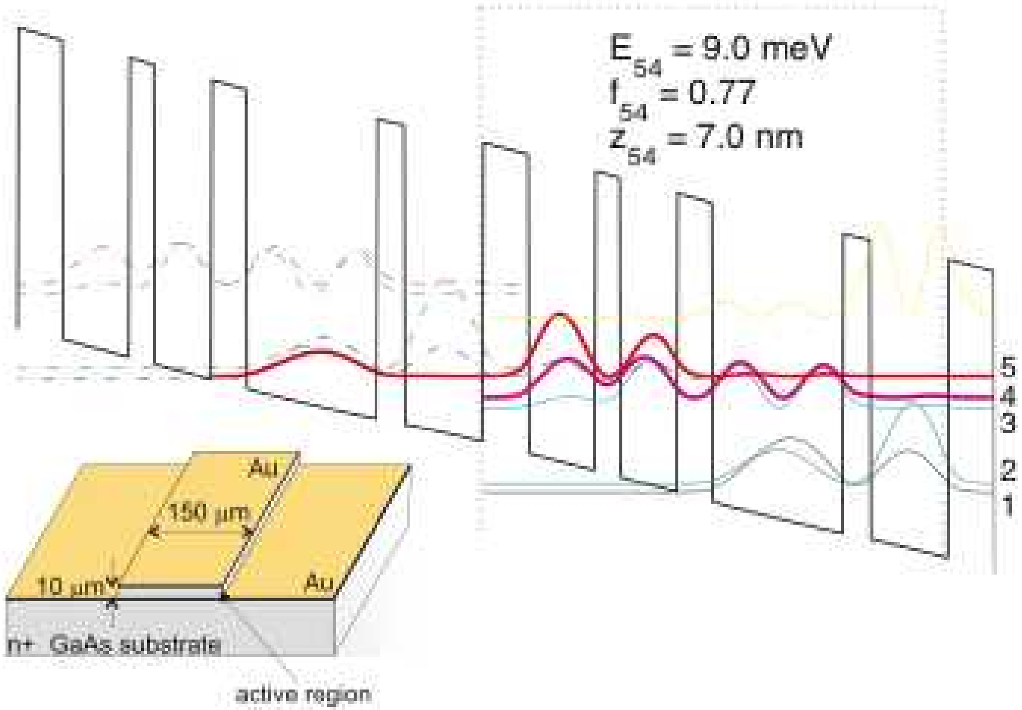
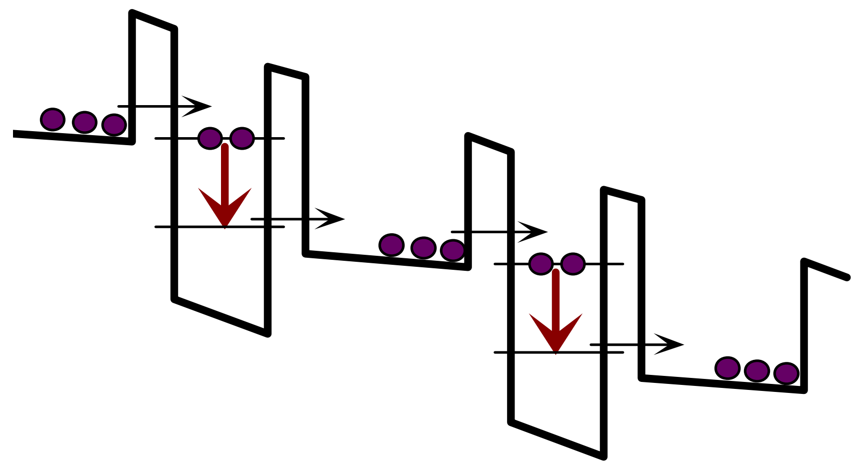
THz Sources: Multipliers



Tretyakov et. al., Int. Journal of IR and mm waves, 20, 1443

THz Sources: Quantum Cascade Laser





- **Repeat the unit cell**
  - **Recycle the electrons**
  - **Increase gain**

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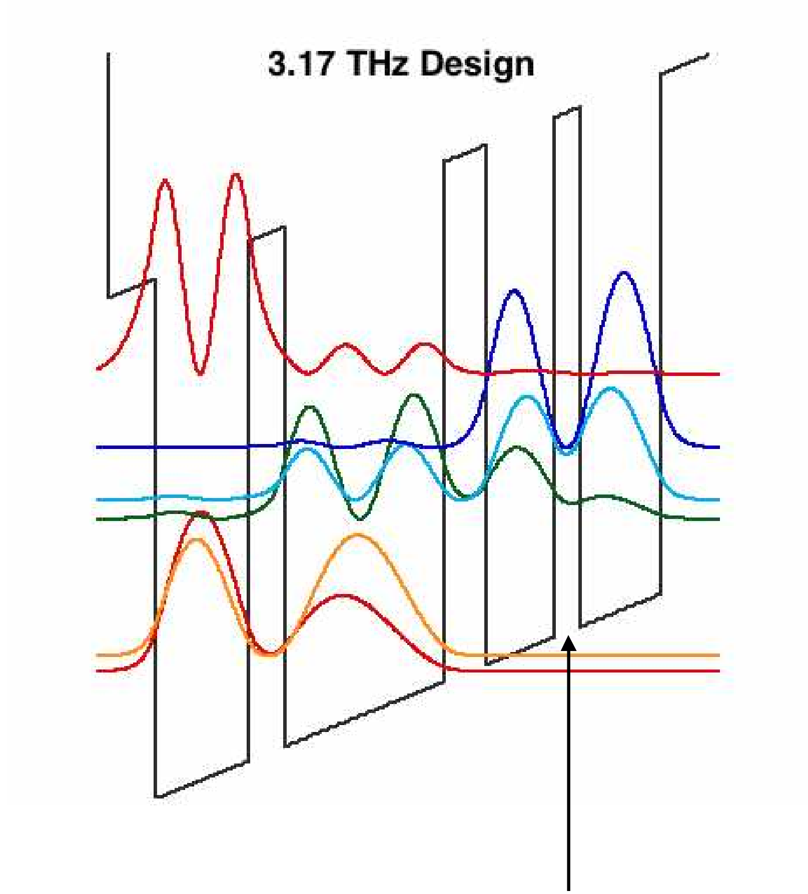
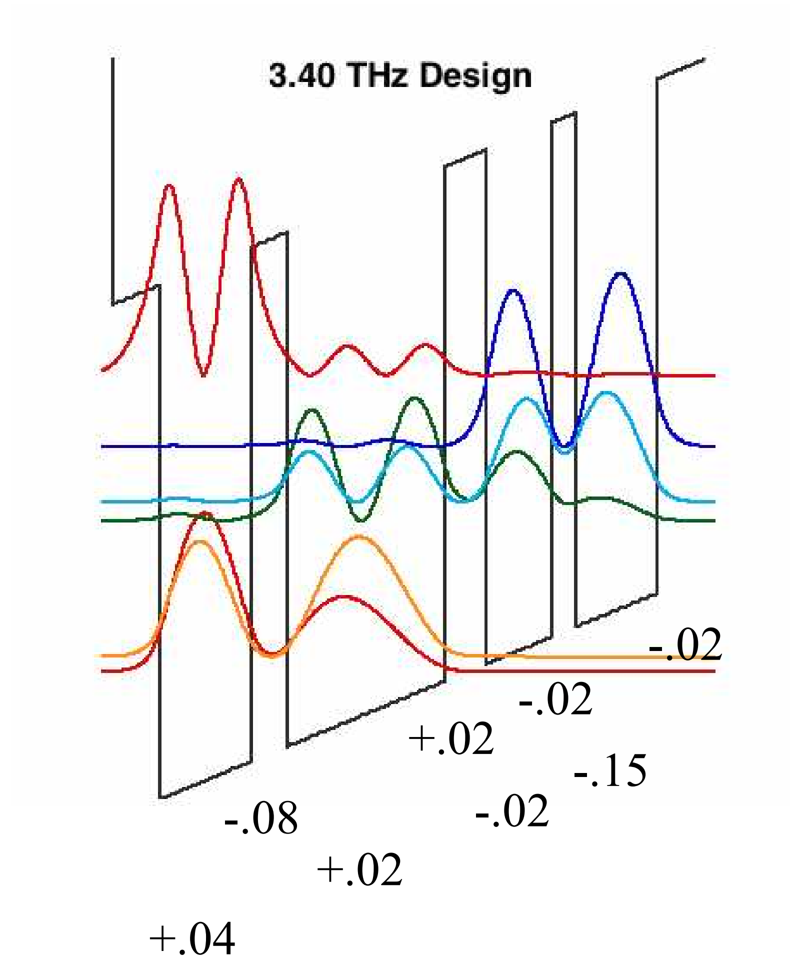
Significance of Layer Thickness



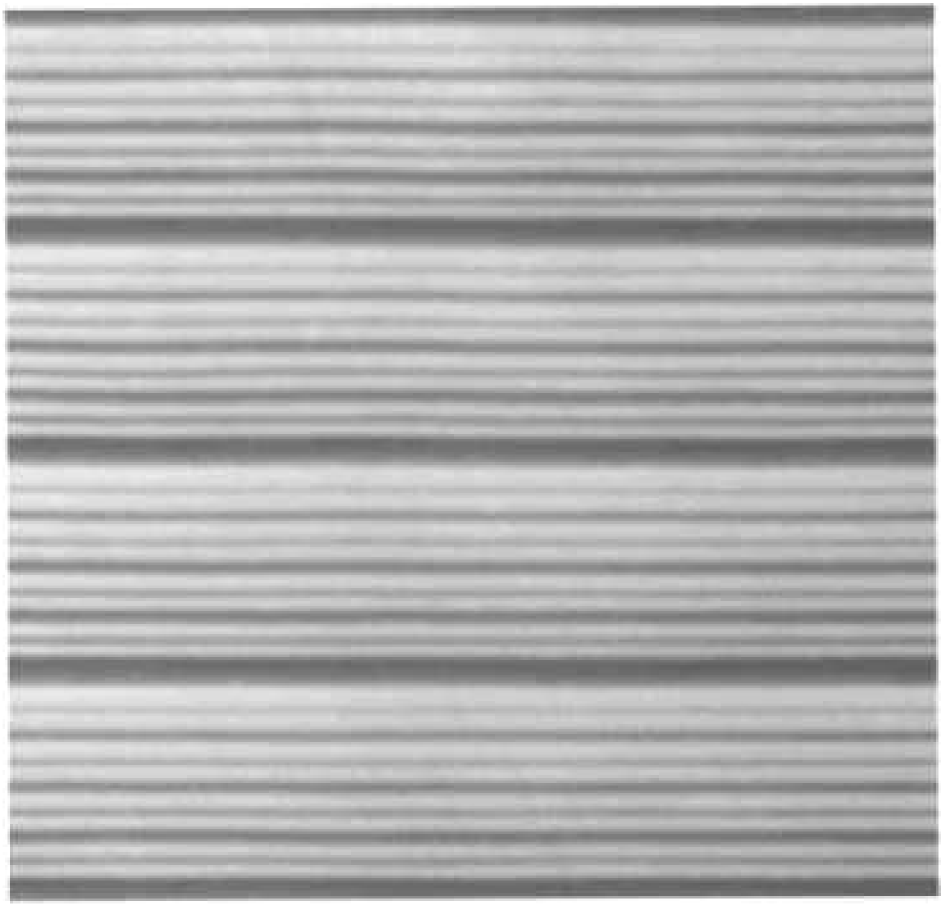


Decrease by 2 ML shifted wavelength from 100µm to 141µm (MIT)

Sub-nanometer control required for frequency control

THz Sources: QCLs
Good growth is key

Lots of Periods



276 Å period

4 Å barrier

Dark - AlInAs
Light - GaInAs

John Reno, Sandia National Labs
→One of the few THz QCL growers in the US

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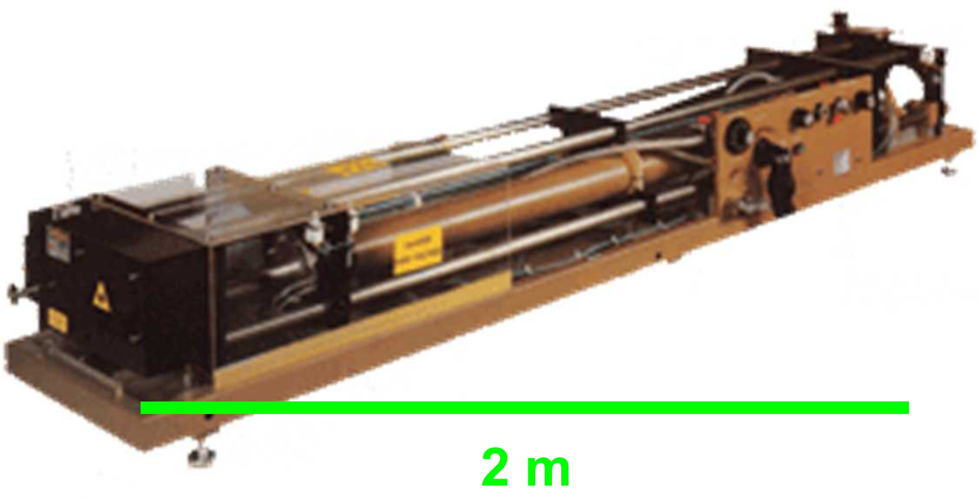
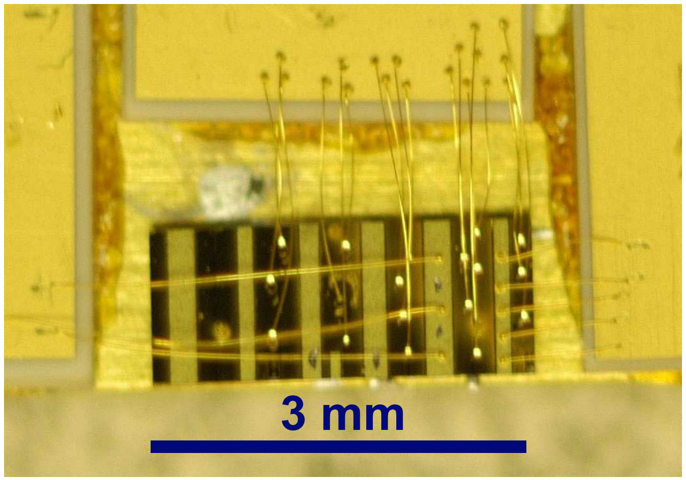
THz Sources: QCL
Why?





- Well Proven
- Large
- Heavy
- 50mW->150mW power

- 2 mm x 0.1 mm,
- 1 gram
- Multiple wavelengths
- 10 mW LO power
- Scalable to mass production
- Potentially low cost

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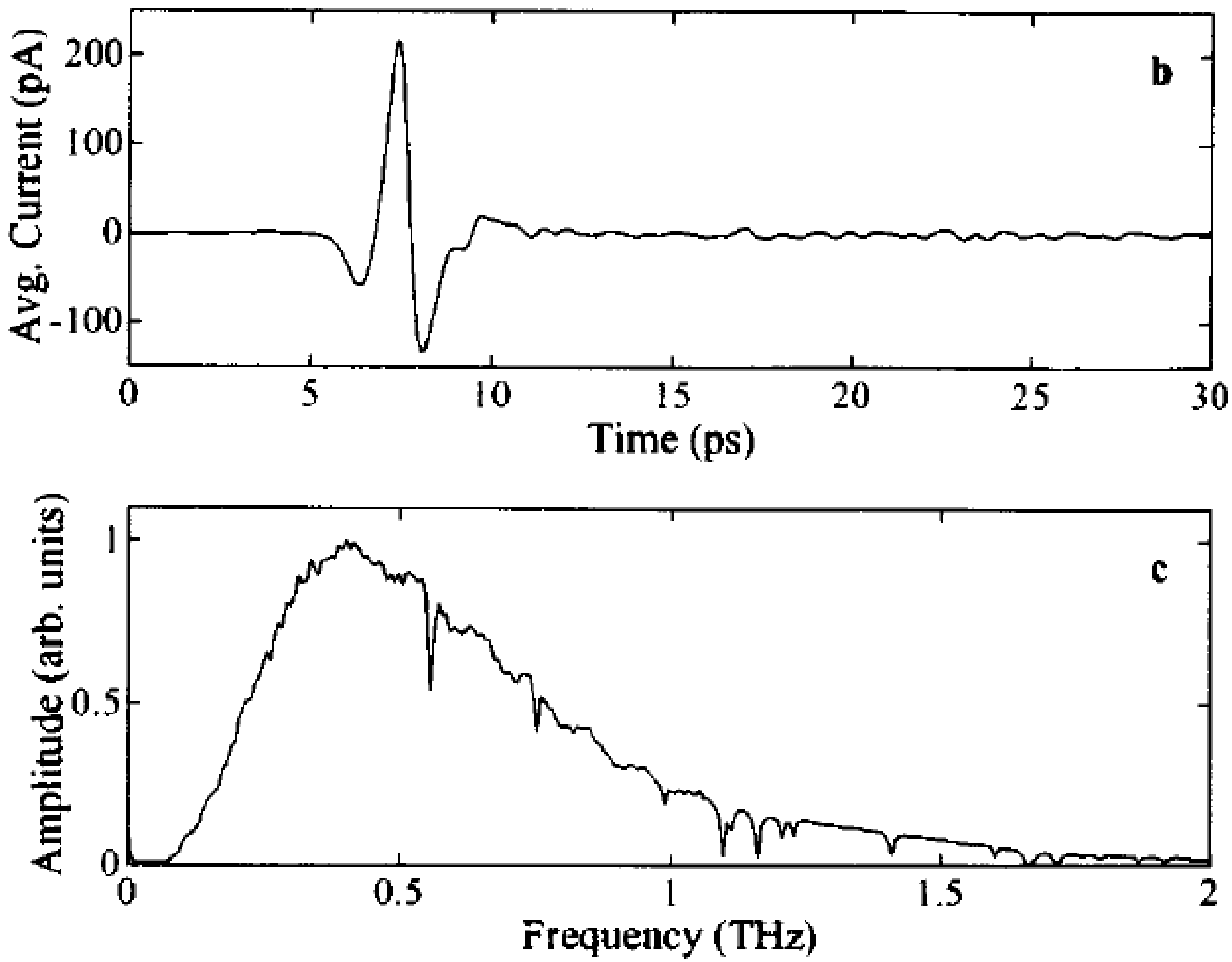
THz Sources: Optical Switches



Cheville, SPIE 5411, 196

THz Sources: Optical Switches

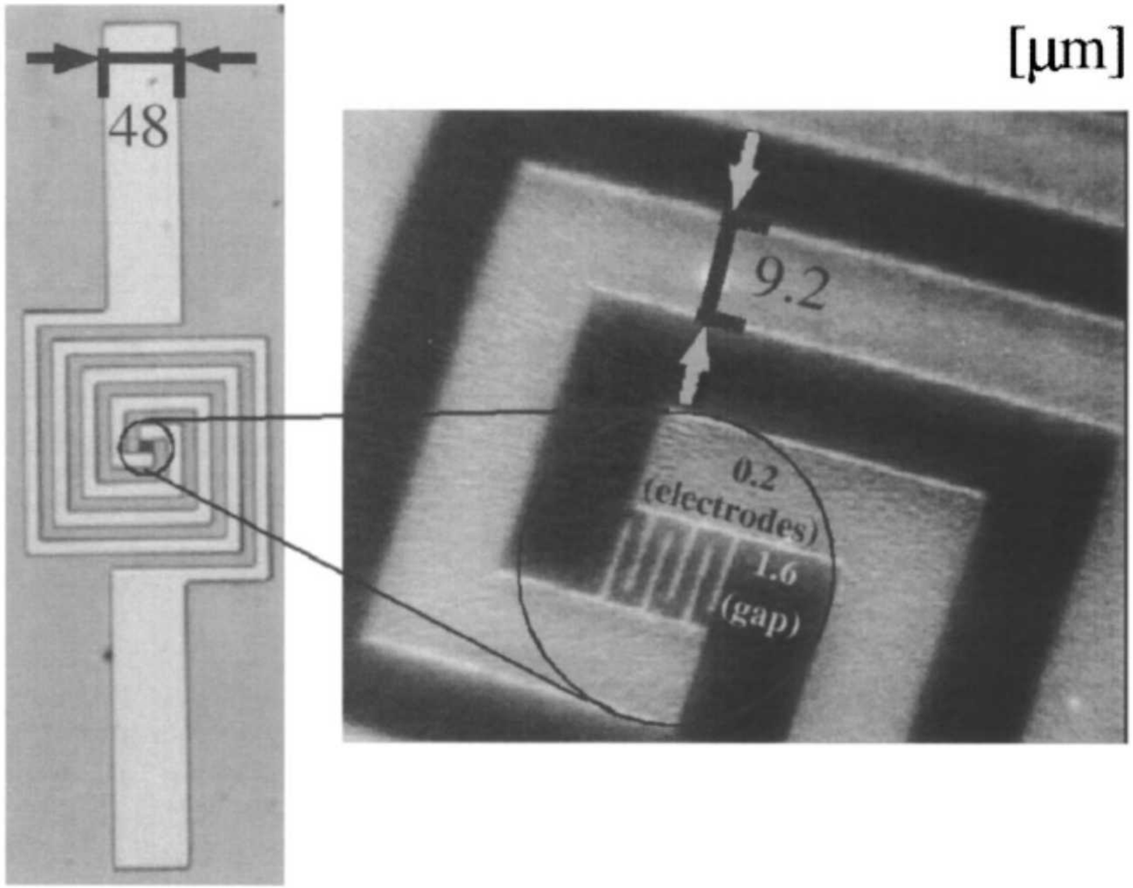
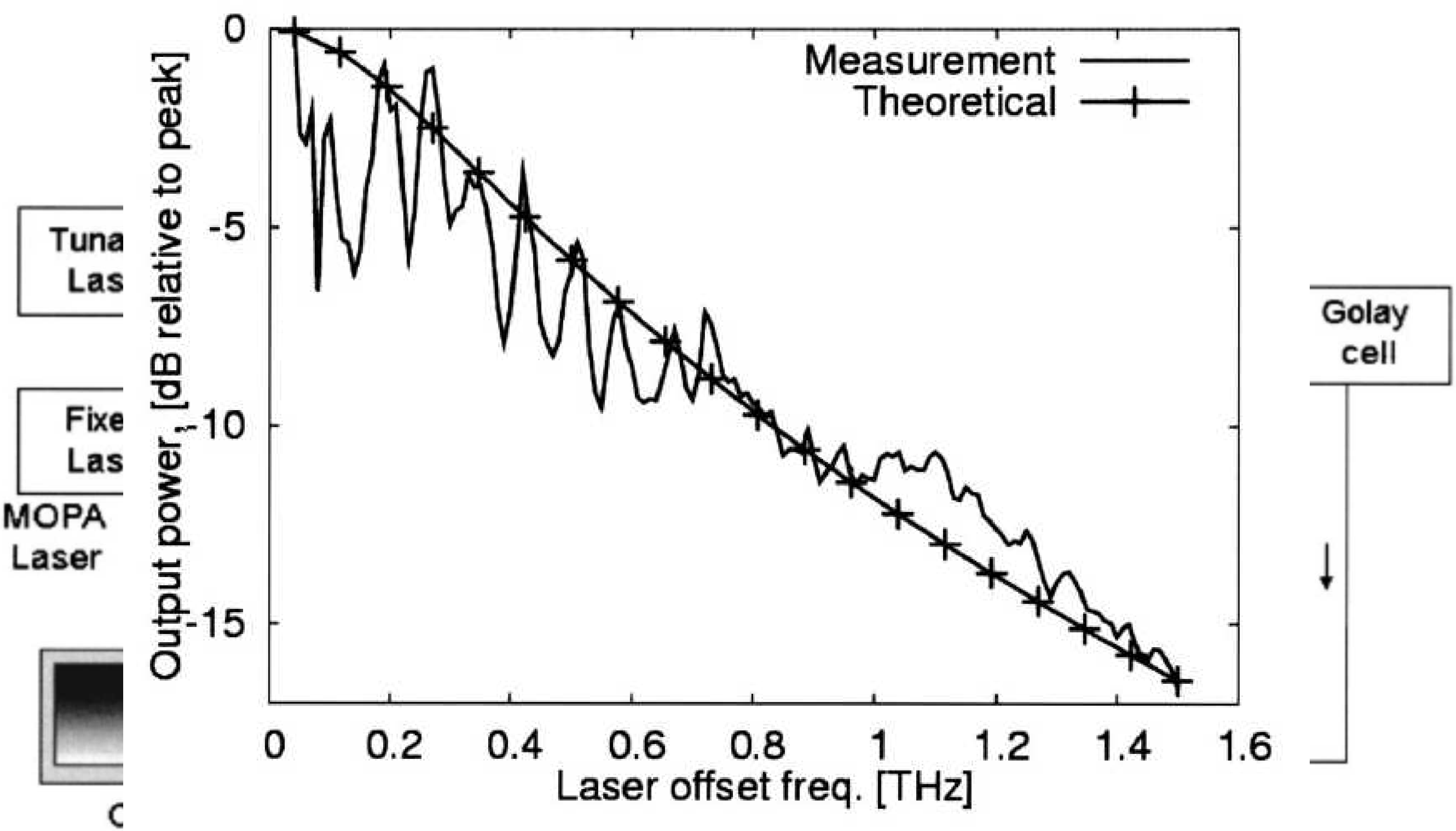


FIG. 1. Photographs of spiral antenna (left) and interdigitated fingers (right). The fingers are 0.2 μm wide and separated by 1.6 μm.

Bjarnson, etal, APL 86, 3983

THz Sources: Optical Switches



Bjarnson, etal, APL 86, 3983

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- **THz Detectors**
- Plasmon FET THz detectors
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THz Detectors: What is Noise Equivalent Power (NEP) and why should I care?

- Definition
  - Noise(V/√Hz) / Responsivity(V/W) =W/√Hz
- Example
  - Measure with a 1Hz bandwidth
  - Say NEP = 1uW/√Hz
  - Signal-to-noise = 1 for 1uW incident power
- Importance
  - Electronics can't help you if you have a lousy NEP!

THz Detectors

- Schottky Diode
  - NEP 10^{-10}W/√Hz
- Pyroelectric
  - Cheap, good for general purpose lab use
  - Typically slow, < 100Hz NEP 10^{-9}W/√Hz
- Nb Bolometer
  - Hot electron bolometer, ns response times
  - NEP 10^{-9}W/√Hz to 10^{-13}W/√Hz
- Silicon Bolometer
  - Slow, typically operate at 400Hz
  - NEP $10^{-12,13}$W/√Hz
- InSb bolometer
  - Use a magnetic field (permanent magnet)
  - Hot electron bolometer, 1μs response times
  - NEP 10^{-12}W/√Hz
- Impurity Band Detectors (Gallium doped Germanium)
  - 50kHz, NEP 10^{-13}W/√Hz
- Quantum Hall Effect Detector (Kalugin, NM Tech)
  - Response times 10ns to 50ms, NEP~10^{-14}W/√Hz

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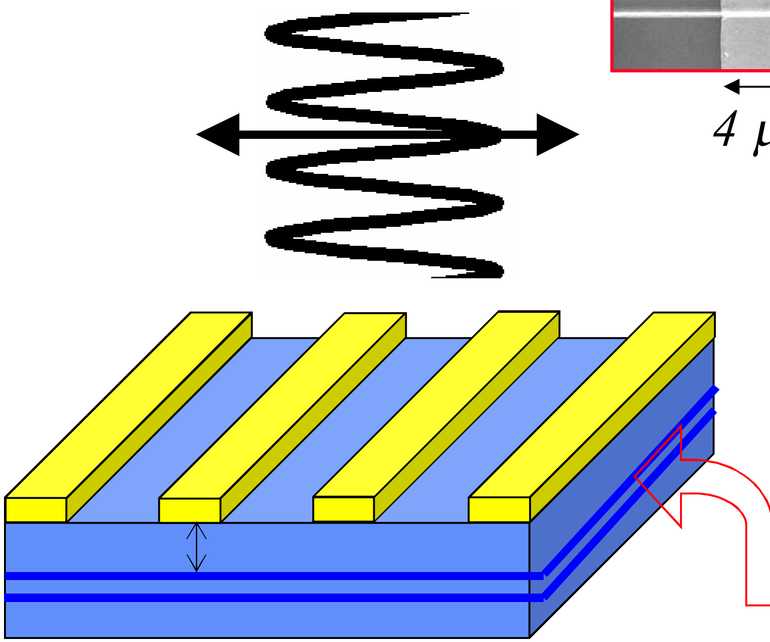
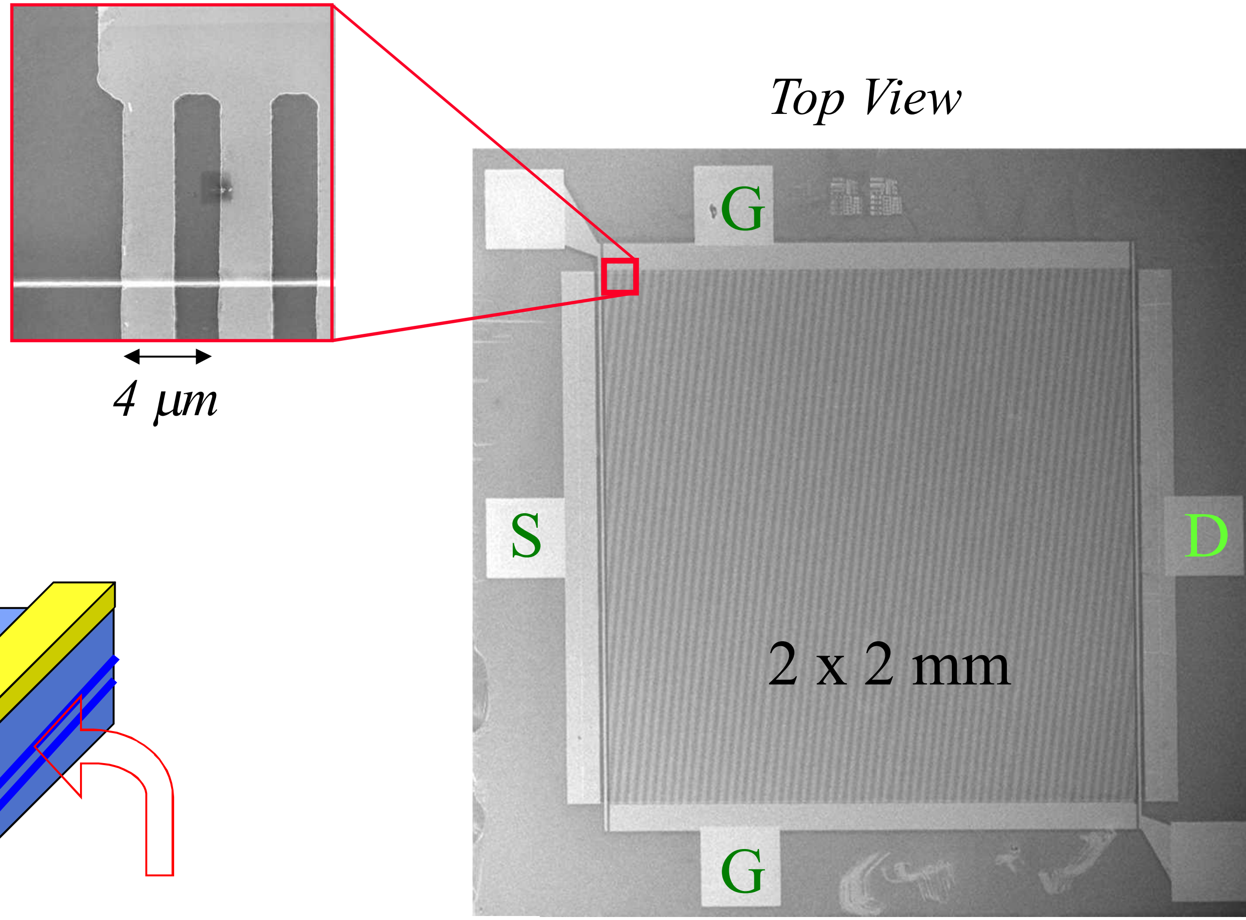
Plasmonic FET: Grating Gate Detector



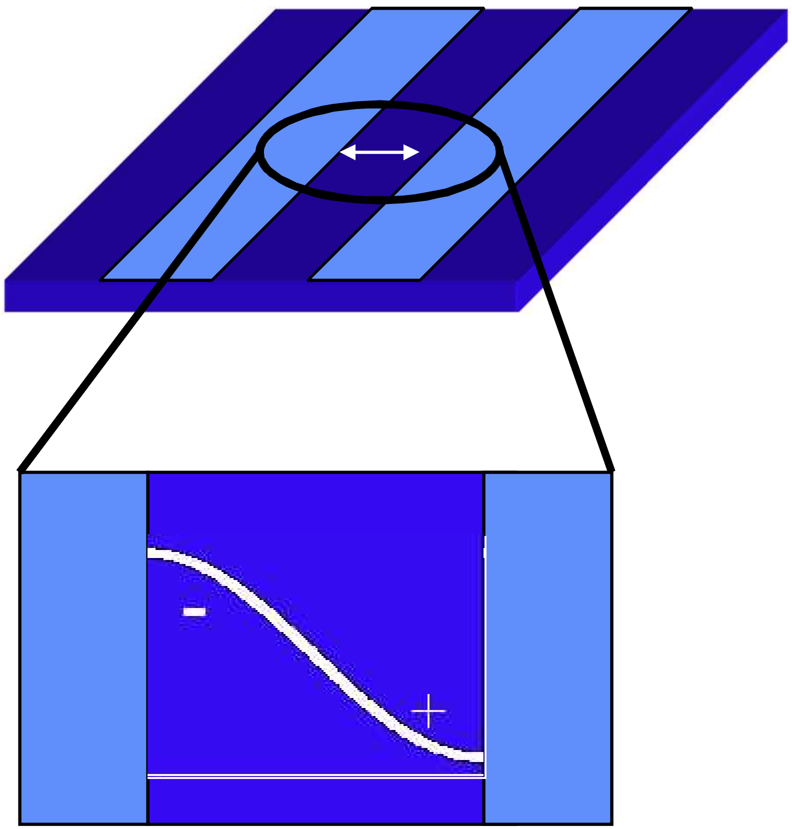


GaAs/AlGaAs
Single or Double Quantum Wells

Plasmonic FET: Plasmons

- **Collective oscillation of electrons**

Sea of electrons



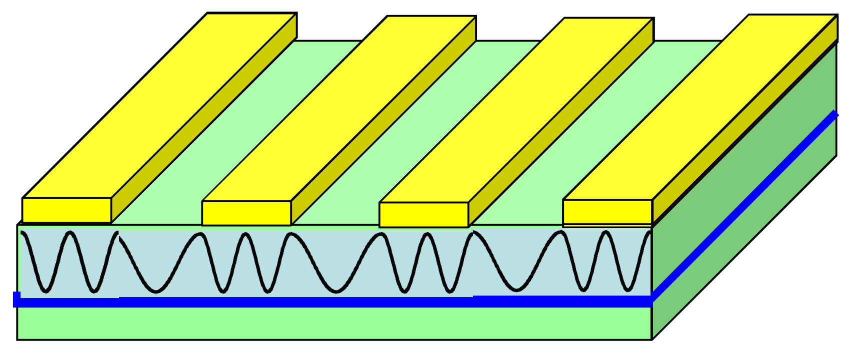
Plasmon Resonance

Plasmon frequency dependence

$$f_p^2 \propto n(V_G)k_j$$

Carrier density   Wavevector

Plasmons in the device



Plasmonic FET: 2D-Plasmons
More than one wavevector is accessible

$$f_p^2 \propto n\left(V_{\mathrm{G}}\right)k_j$$

All have the same frequency
n x k = constant

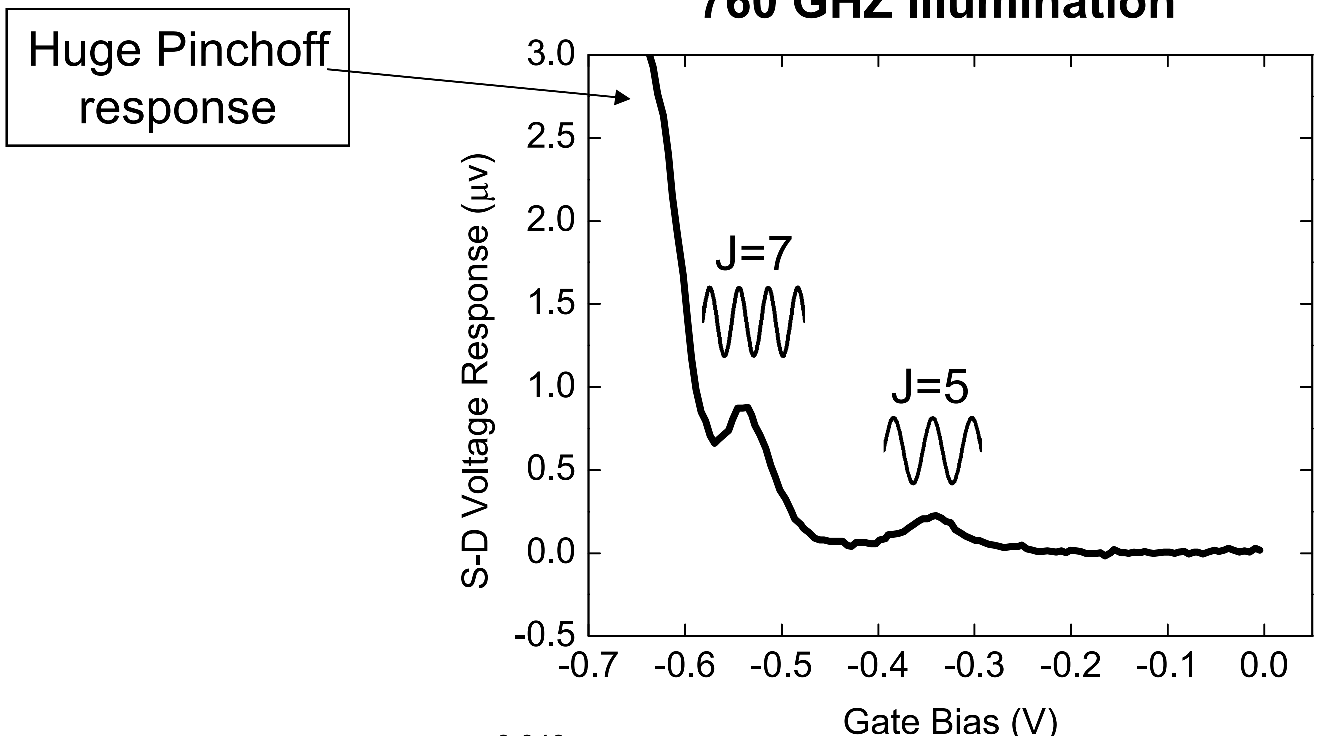
j=1
$k=k_1, n=n_1$

j=2
$k=2k_1$, $n=n_1/2$

j=3
$k=3k_1$, $n=n_1/3$

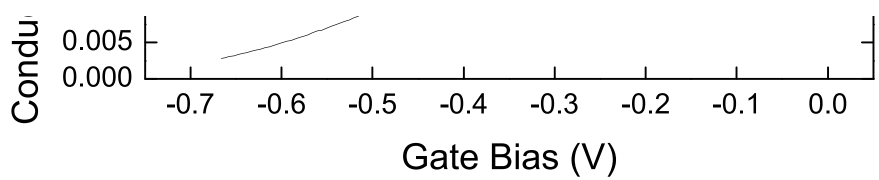
Plasmonic FET: Operating Modes and Performance

760 GHZ Illumination



Few mV/W tunable responsivity

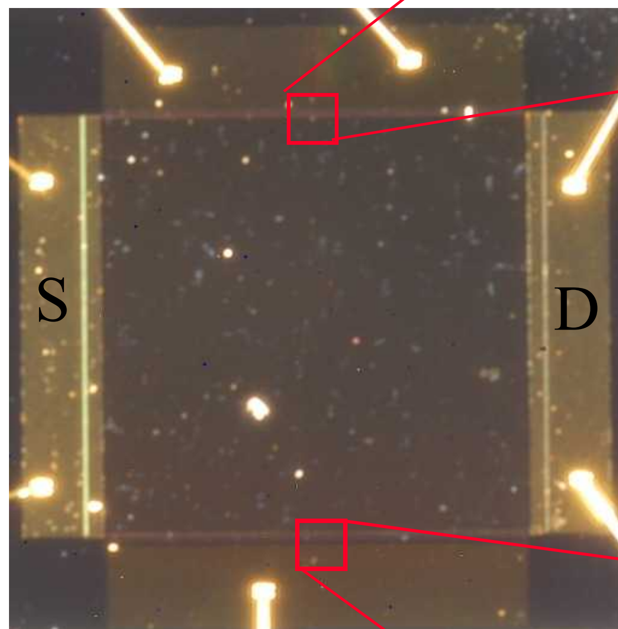
NEP ~ 10^{-5} W/√Hz

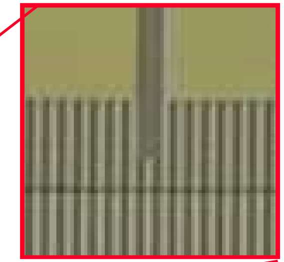


Plasmonic FET:
The Split-Grating Gate Detector

- Bulk gates biased at plasma frequency (defines absorption frequency)

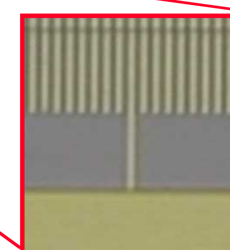
- Single gate line biased to depletion





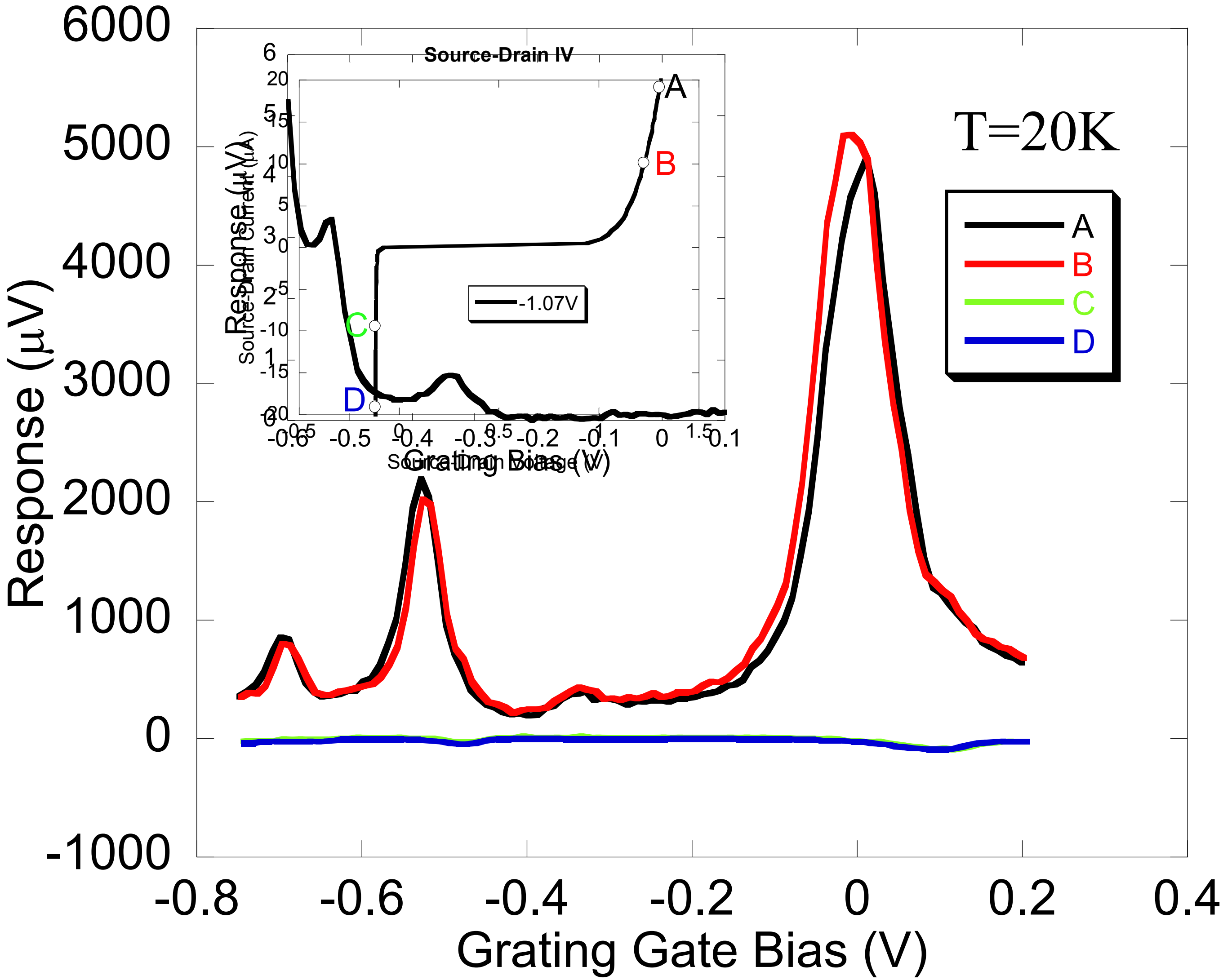
Biased to plasma resonance
Tunable

Biased to depletion
Responsivity



Desired Benefits
- responsivity of pinchoff mode
- tunability of plasma resonant mode.

Split-gate Photoresponse
694 GHz, 1.5mW power



Split-gate SQW Detector Responsivity few V/W

Photoresponse is NOT "diode like"

→ 3 orders of magnitude improvement!

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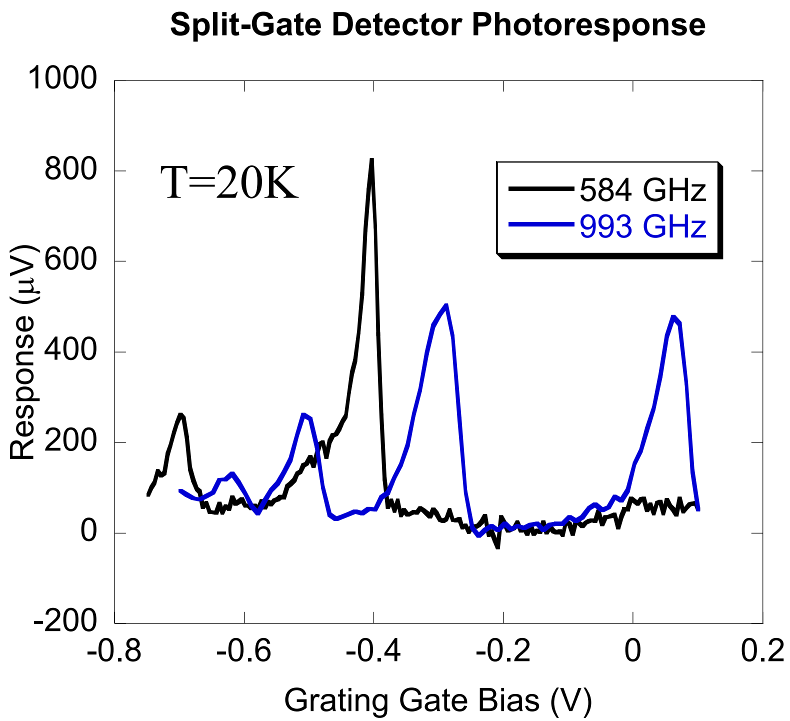
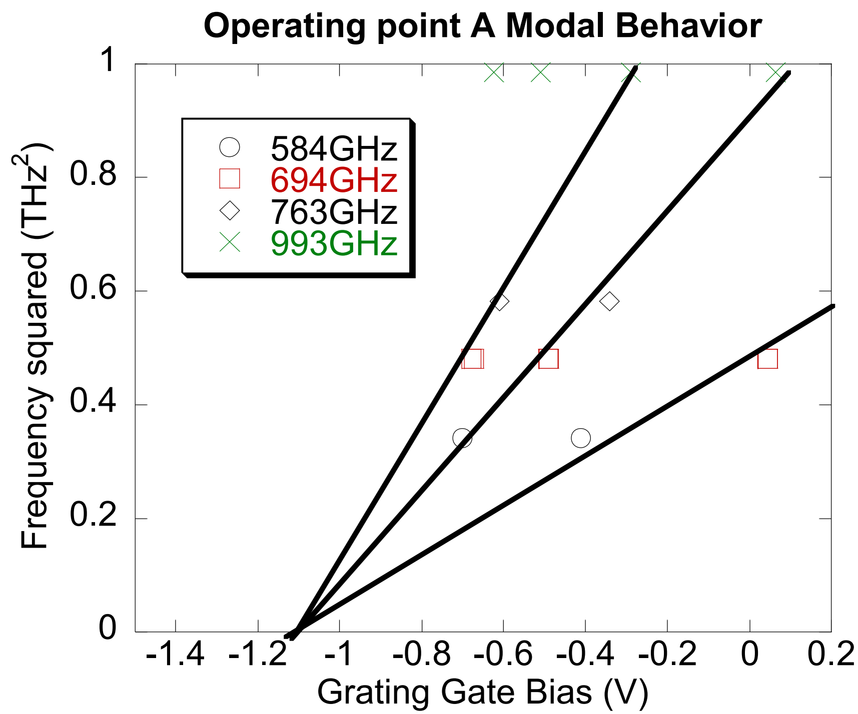
Plasmonic FET:
Split-gate detector Tunability





Detectors retain tunability

NEP ~ 10^{-7} W/√Hz

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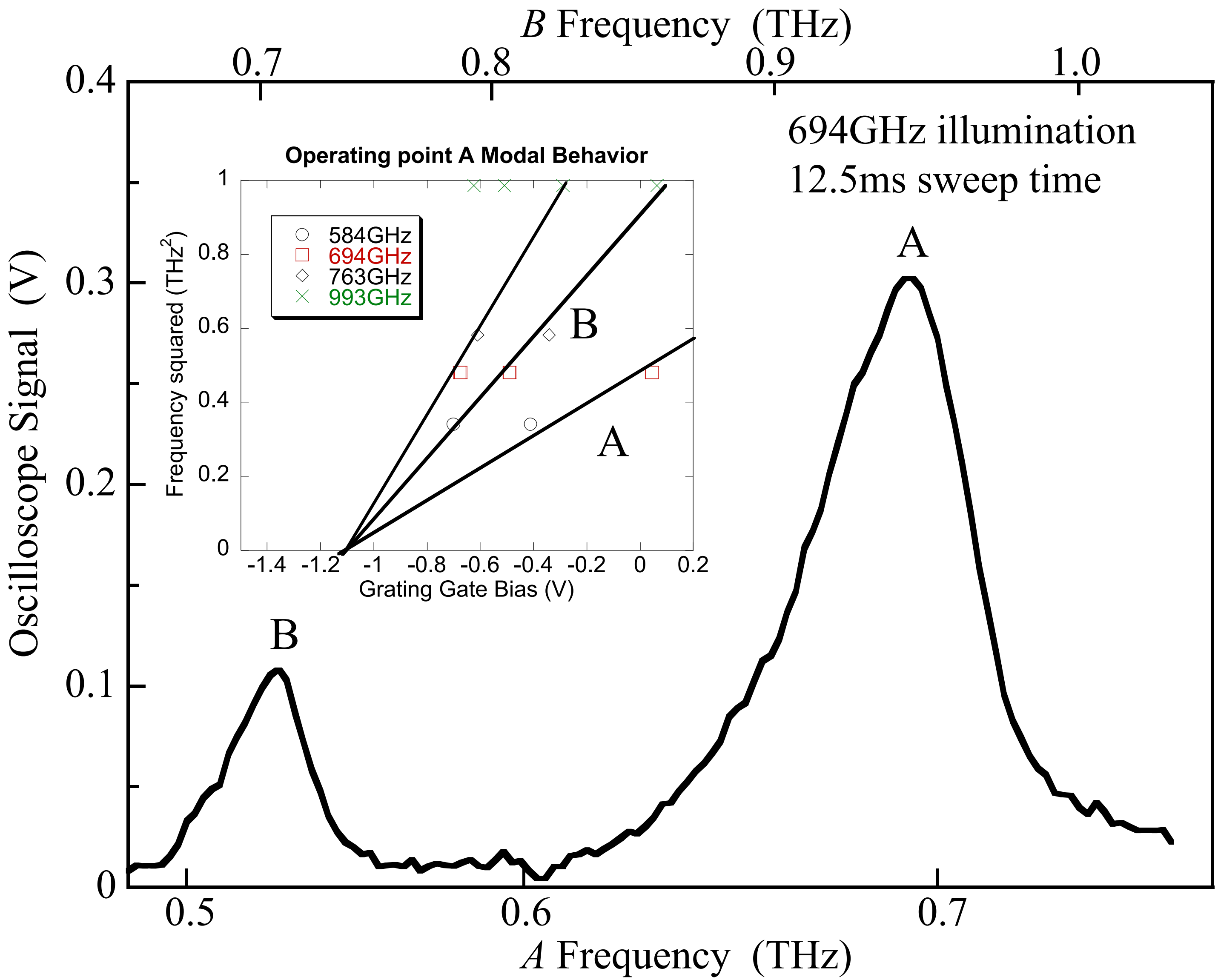
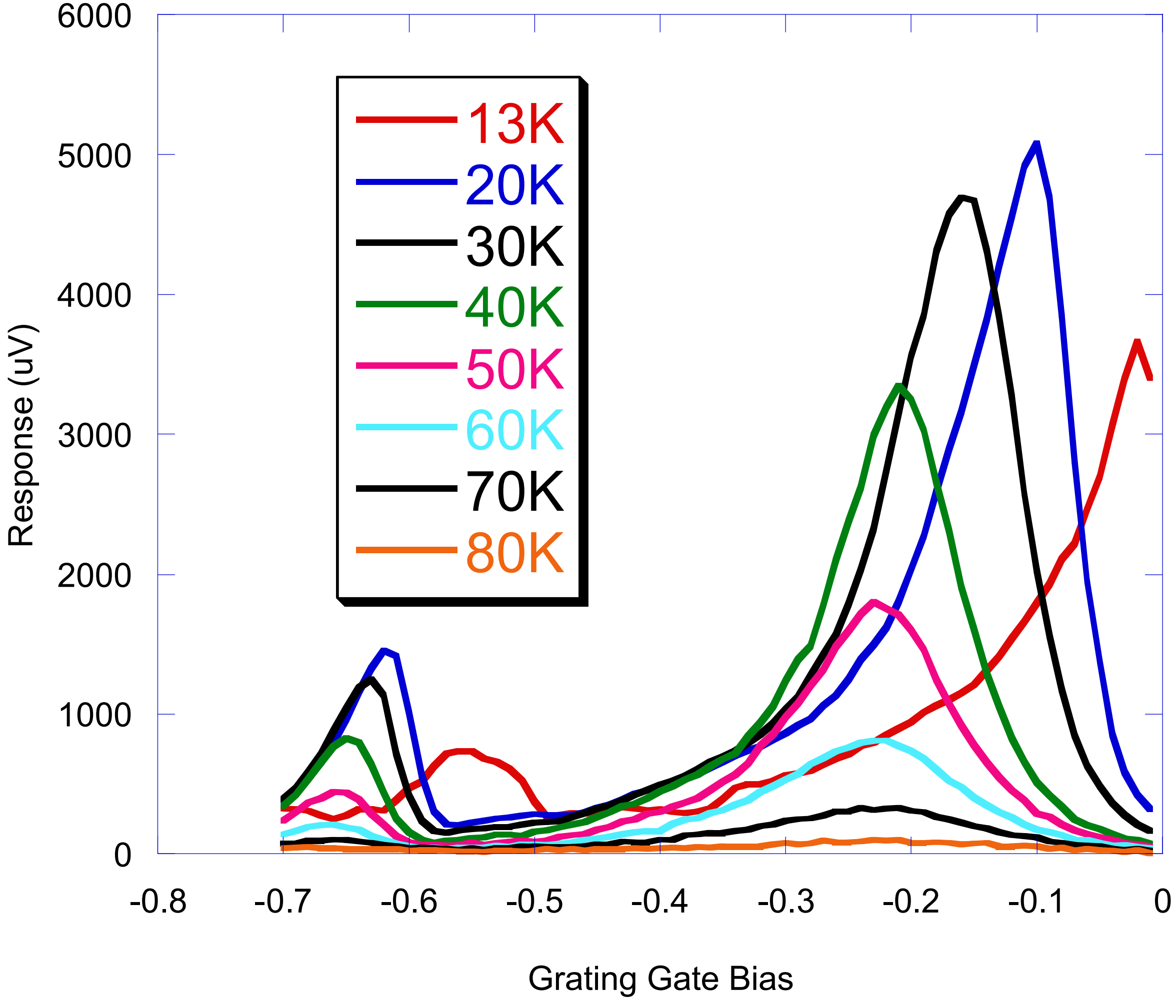
Plasmonic FET: 'Rapidly' sweepable spectroscopy



Plasmonic FET: Temperature Dependence

Split-grating gate detector, 694 GHz excitation



Noise goes down as temperature goes up!
What does that mean?

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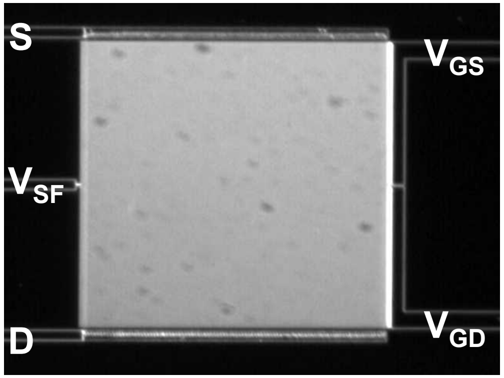
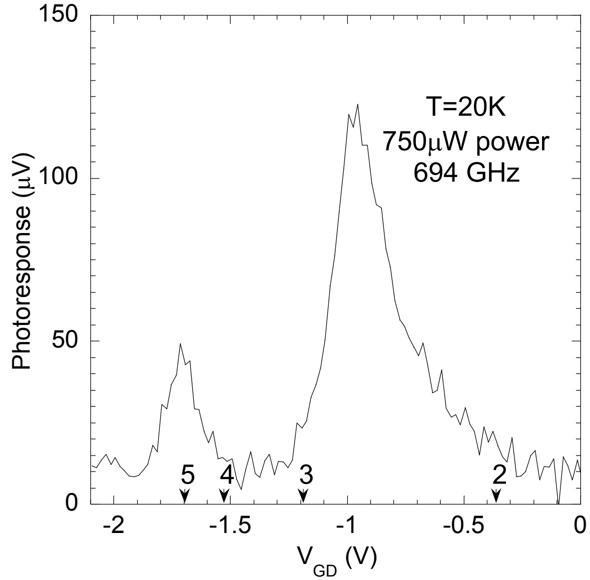
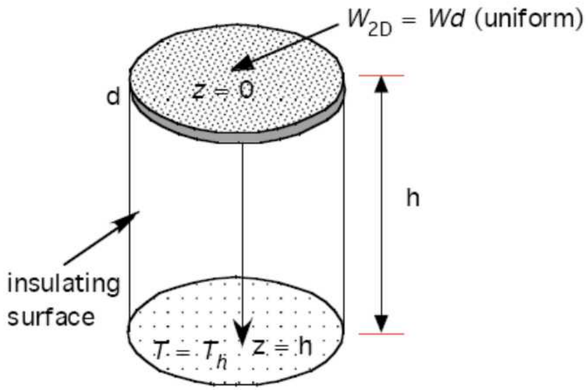
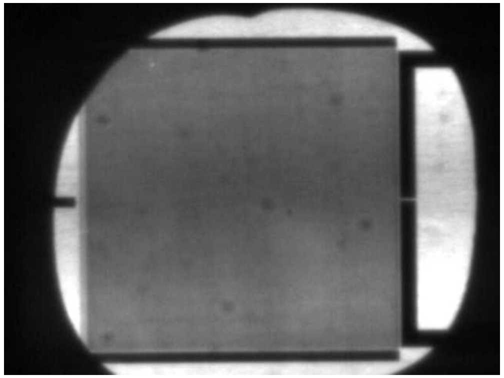
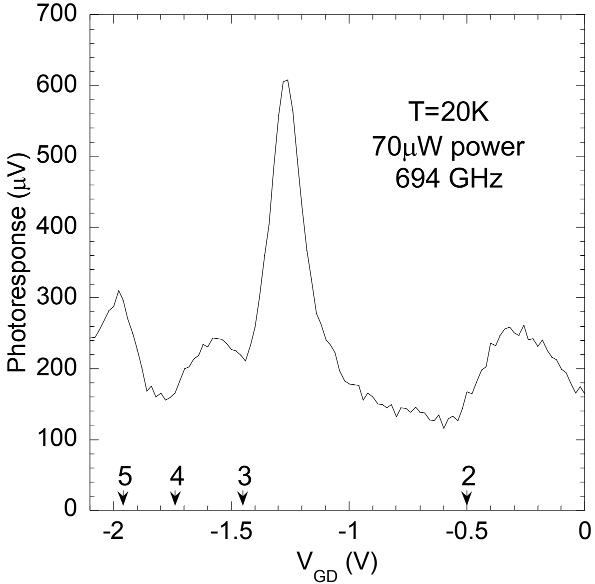
Split-Gate Detectors fabricated on thermally isolating membranes

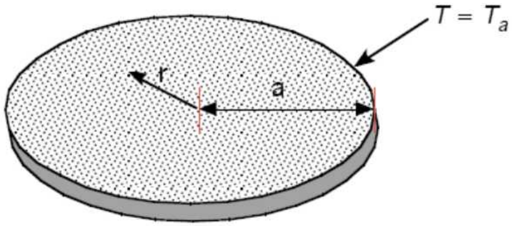












Simple theory: 40x enhancement
Experiment: 50x enhancement

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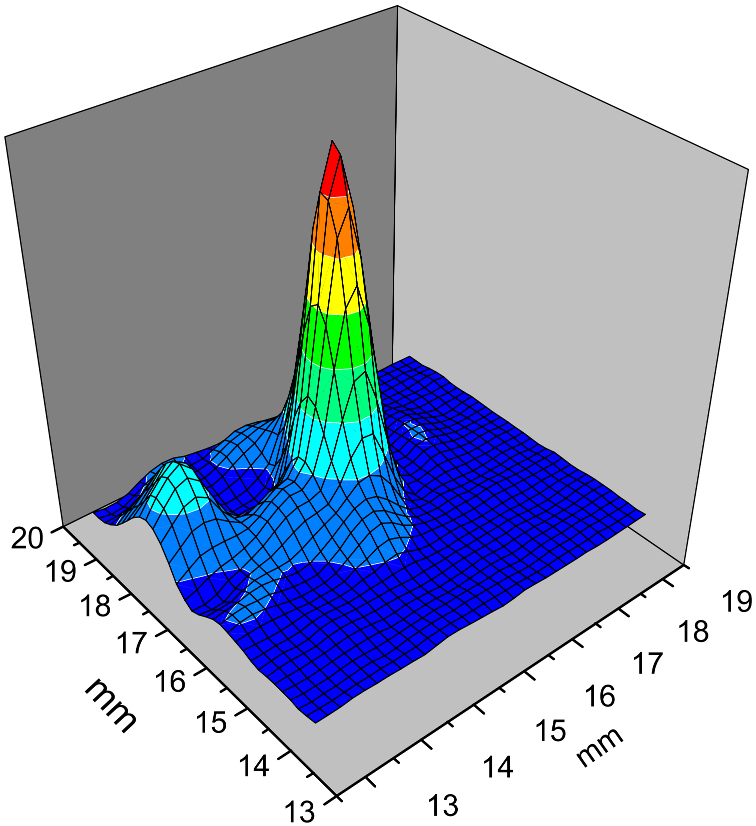
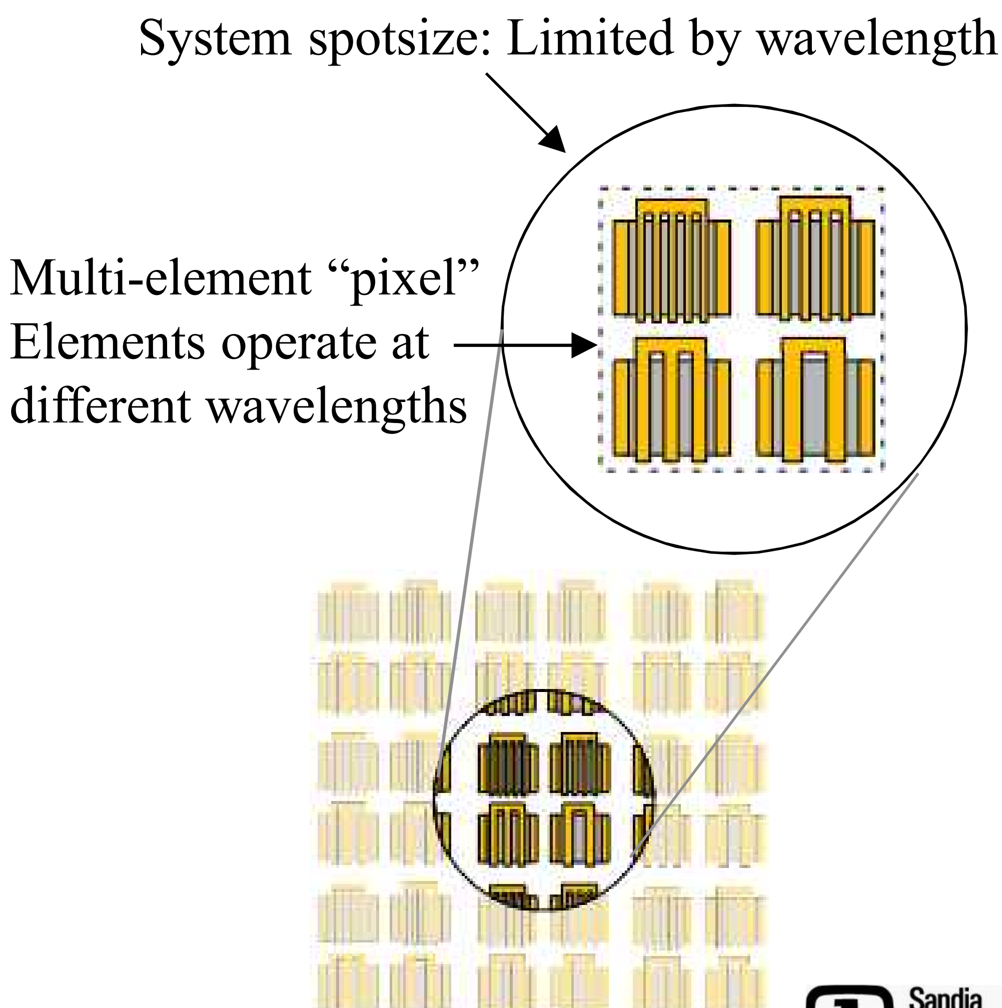
Plasmonic FET: Future Outlook
Sub-wavelength detectors enable multi-spectral imaging

200um x 200um Detector
Beam Image

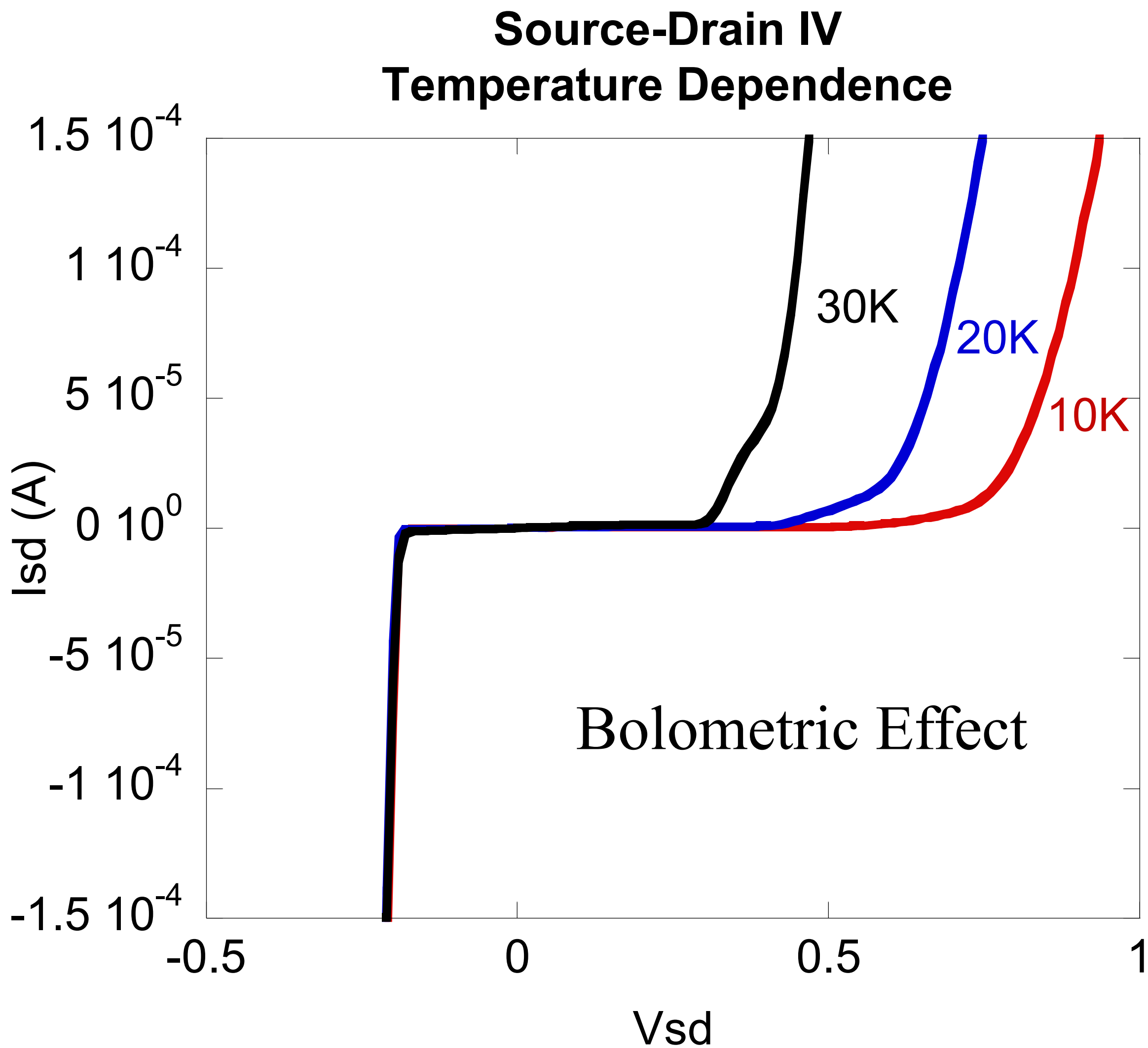




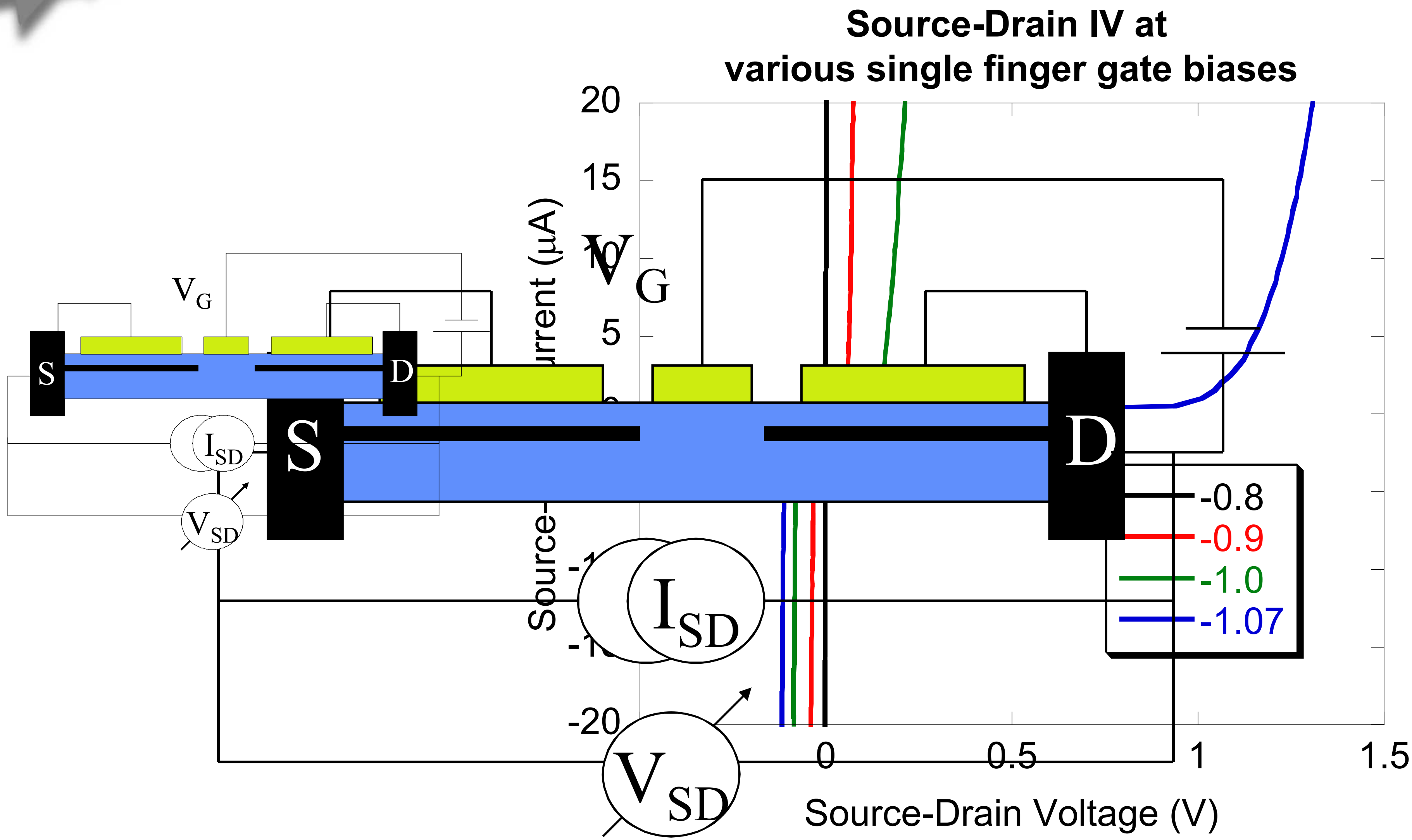
Conclusions

- In 5-10 years, probably won't be able to call the THz undeveloped anymore.
- Several companies currently make THz spectrometers
- Many combinations of sources/detectors have been used for creating THz images
- It is not clear that there will be a 'winning' combination of sources/detectors. More likely source/detector pairings for specific applications

Plasmonic FET: Origin of large Photoresponse



Plasmonic FET:
Split Gate Detectors IV Characteristics



What is going on?

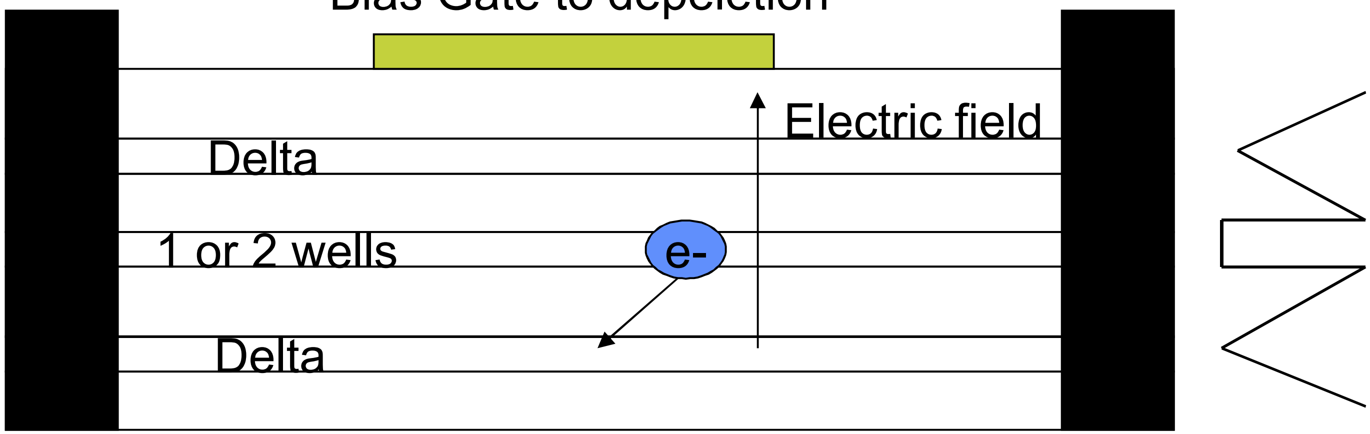
Real-Space Transfer

Electrons fired over QW edge gets pushed to delta

S

D

Bias Gate to depeletion



Thermionic Field Emission

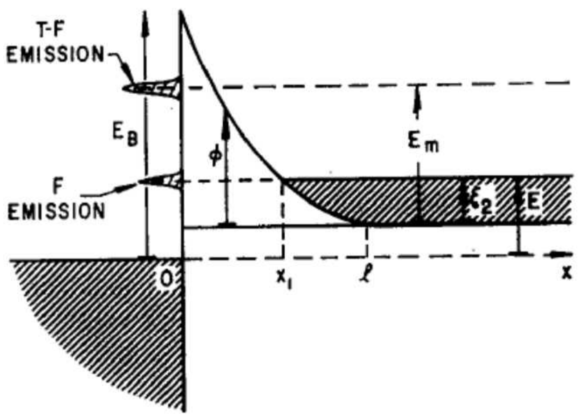
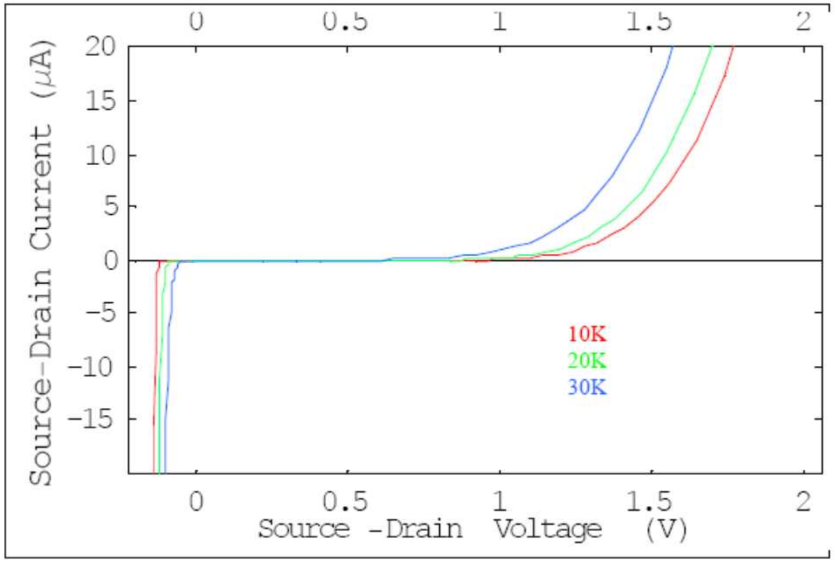


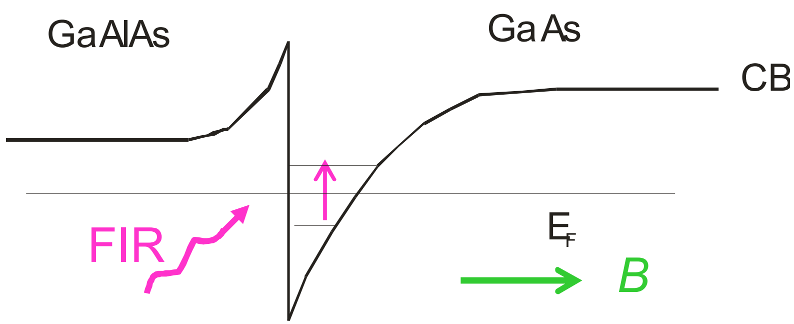
FIG. 1. Electron potential energy diagram of a forward biased Schottky barrier.

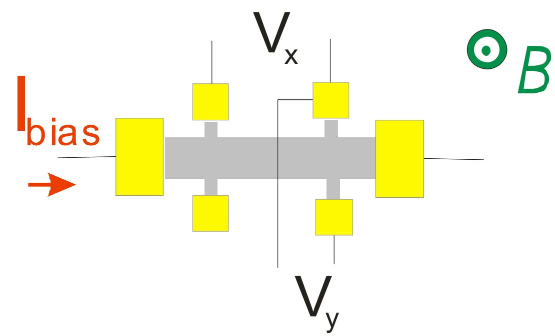
Padovani & Stratton, <u>*Solid State Electronics*</u>, 9 (695), **1966**



Greg Aizin (CUNY)

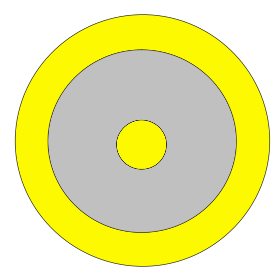
THz Detectors: Quantum Hall Detector





Hall bar

meander



Corbino device

THz Detectors: Quantum Hall Detector

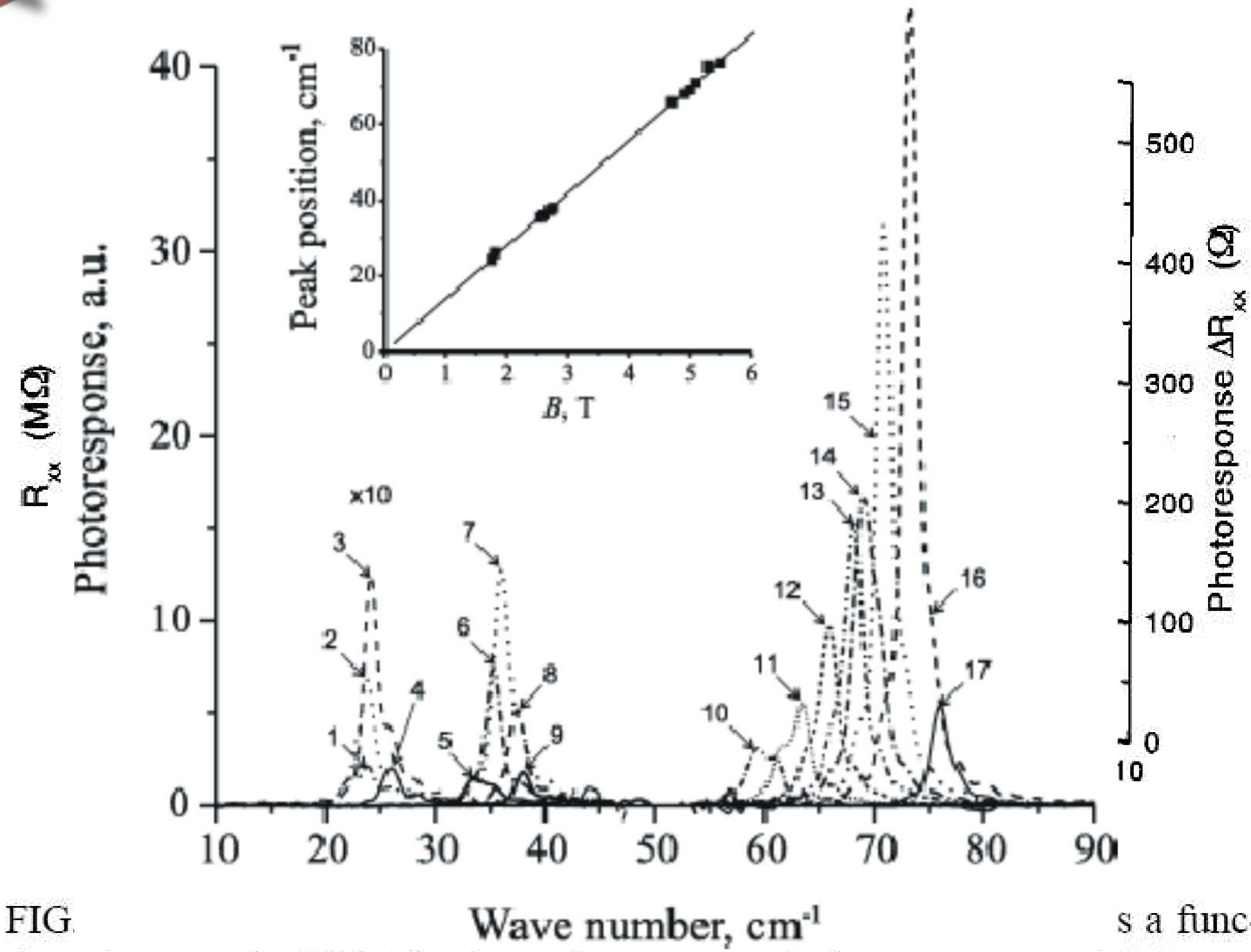


FIG. ... s a function of magnetic field. The inset shows an excitation spectrum of ΔR_{xx}.

Nikolai Kalugin, NM Tech

Y.Kawaguchi, K.Hirakawa, M.Saeki, K.Yamanaka, S.Komiyama, Appl.Phys.Lett.80, 136 (2002)

Tunable by gate and magnetic field

Response times 10ns to 50ms, NEP~10^{-14}W/√Hz

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