# About OMICS Group

**OMICS Group International is an amalgamation of Open Access publications and worldwide international science conferences and events. Established in the year 2007 with the sole aim of making the information on Sciences and technology 'Open Access', OMICS Group publishes 400 online open access scholarly journals in all aspects of Science, Engineering, Management and Technology journals. OMICS Group has been instrumental in taking the knowledge on Science & technology to the doorsteps of ordinary men and women. Research Scholars, Students, Libraries, Educational Institutions, Research centers and the industry are main stakeholders that benefitted greatly from this knowledge dissemination. OMICS Group also organizes 300 International conferences annually across the globe, where knowledge transfer takes place through debates, round table discussions, poster presentations, workshops, symposia and exhibitions.**

# About OMICS Group Conferences

OMICS Group International is a pioneer and leading science event organizer, which publishes around 400 open access journals and conducts over 300 Medical, Clinical, Engineering, Life Sciences, Phrama scientific conferences all over the globe annually with the support of more than 1000 scientific associations and 30,000 editorial board members and 3.5 million followers to its credit.

OMICS Group has organized 500 conferences, workshops and national symposiums across the major cities including San Francisco, Las Vegas, San Antonio, Omaha, Orlando, Raleigh, Santa Clara, Chicago, Philadelphia, Baltimore, United Kingdom, Valencia, Dubai, Beijing, Hyderabad, Bengaluru and Mumbai.

# Carbon-Based Devices for THz Technology

**Mohamed Rinzan, Abdel El Fatimy and Paola Barbara**

Georgetown University

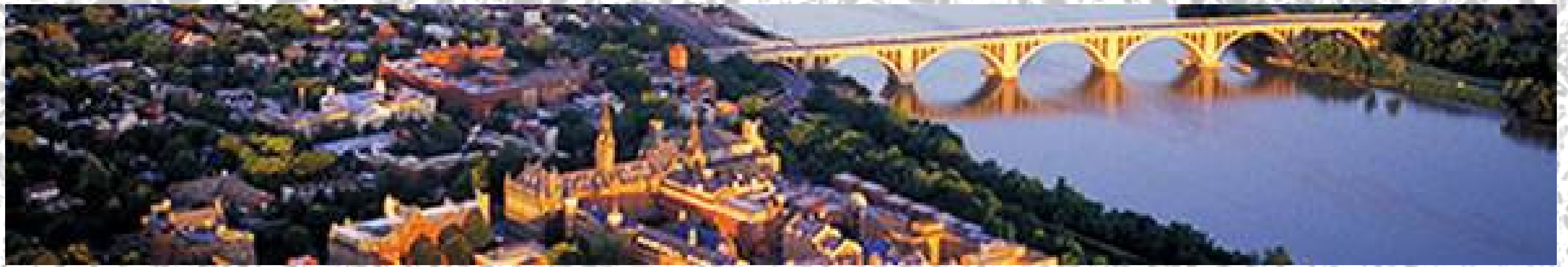
Collaborators:

**Greg Jenkins and Dennis Drew**

University of Maryland

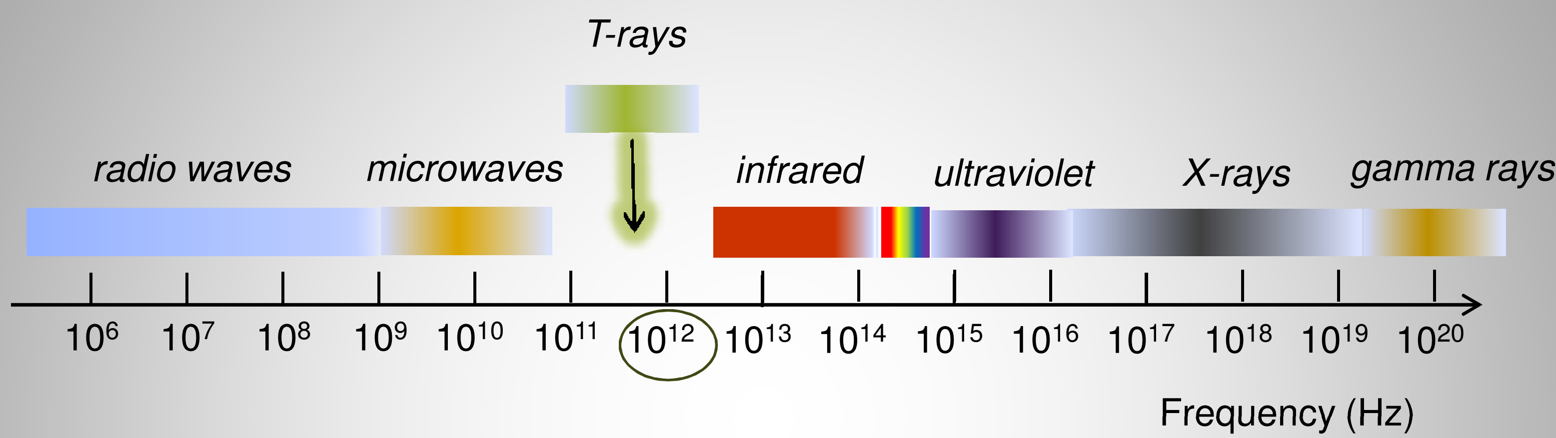
**Serhii Shafraniuk**

Northwestern University



**3RD International Conference on Material Science and Engineering,** San Antonio, TX, USA, October 2014

# T-Rays



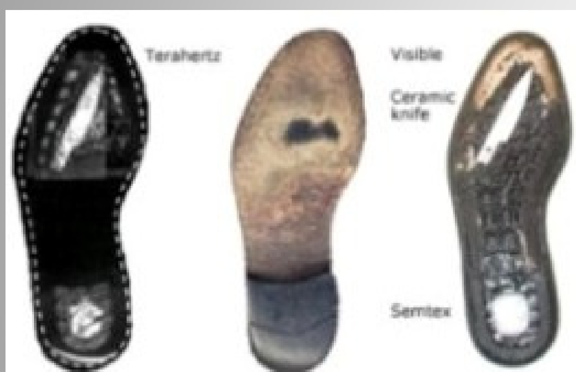


| | | | |
|---|---|---|---|
| frequency | 0.1 THz | ⟷ | 30 THz |
| photon energy | 0.414 meV | ⟷ | 124 meV |
| wavenumber | 3.3 $cm^{-1}$ | ⟷ | 1000 $cm^{-1}$ |
| wavelength | 3 mm | ⟷ | 10 μm |

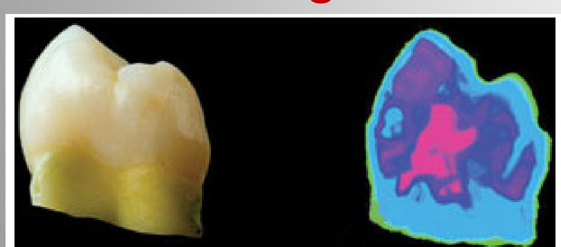
# THz Applications

## Imaging

**Security applications**



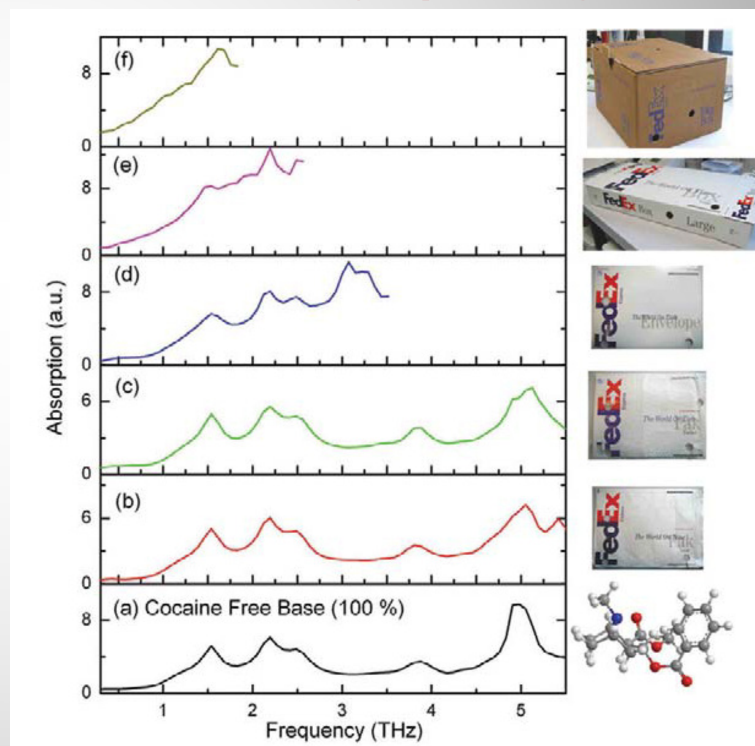

**Medical diagnostics**



TeraView , www.teraview.com

## Spectroscopy

**Chemical fingerprinting**

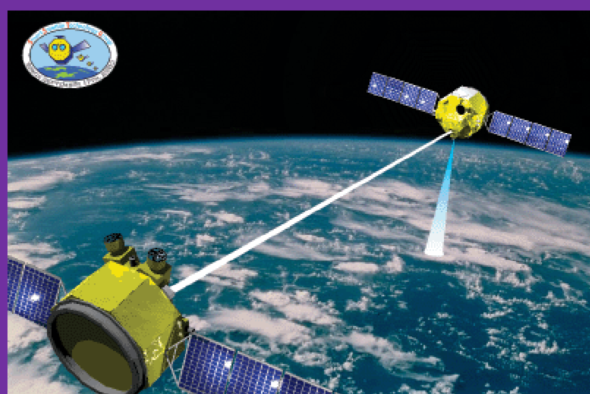



A. G. Davies et al. Materials Today, **11**, 18 (2008)

# THz Applications

## Communication

- **Satellite-satellite**
- **Secure short-range**



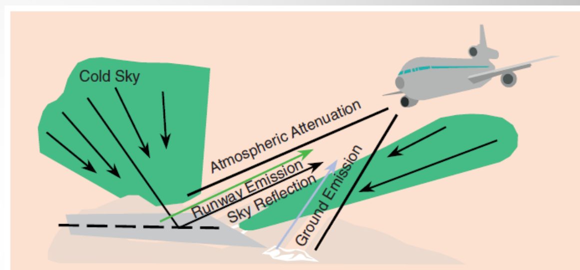
National Institute of Information and Communications Technology

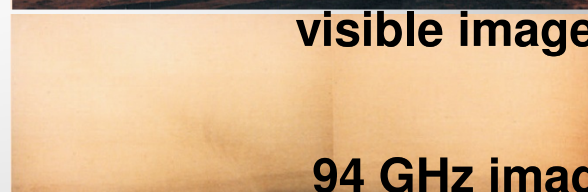
NICT, Tokyo, Japan

L. Yujiri, IEEE microwave magazine **4**, 39-50 (2003)

## Passive Imaging

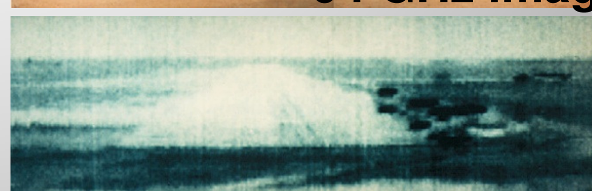
**Dust and smoke conditions**



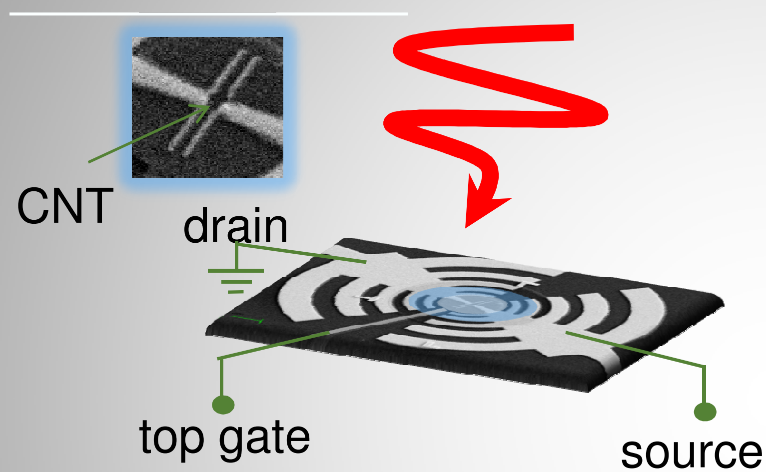



**visible image with fog**

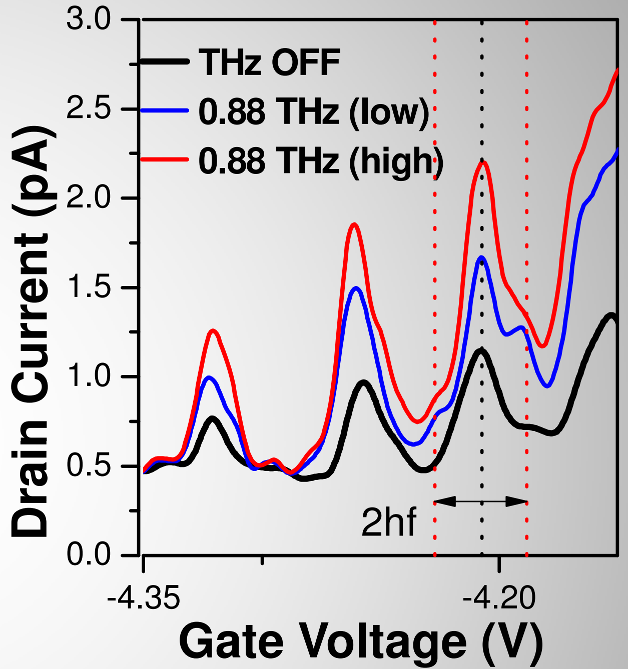
**94 GHz image with fog**



# Quantum Dot Detectors




M. Rinzan et al. Nano Letters 12, 3097 (2012)




## Pro

- **High Sensitivity** (fW)
- **Spectral resolution** (better than 0.1 THz)
- **Broad band detection** (0.6 - 2THz)

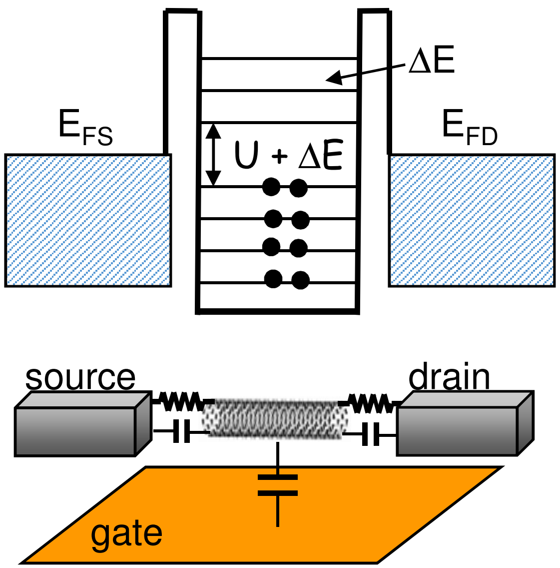
## Contra

- **Low-temperature operation** (10K)
- **Non-linear response**

# Carbon Q-dots

Basic properties:

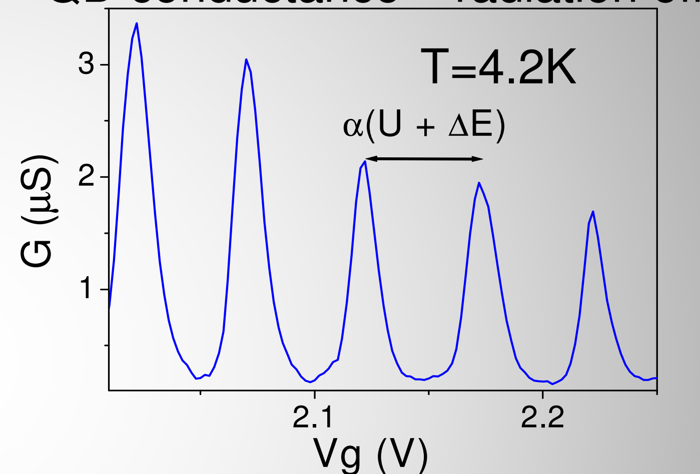
Coulomb blockade and resonant tunneling

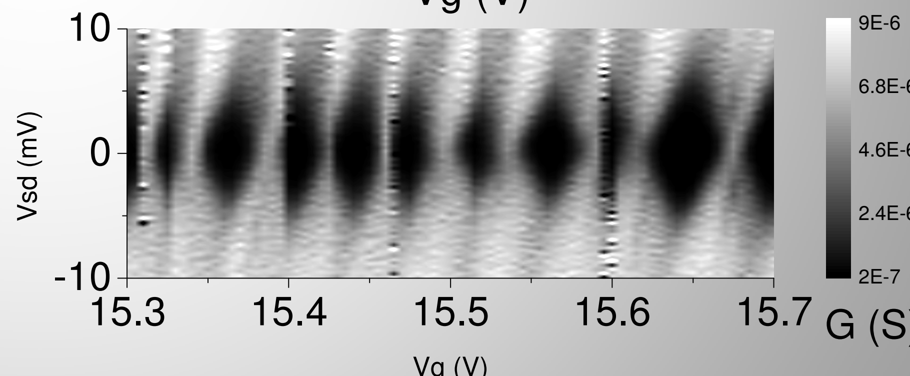



Charging energy: $U = e^2/C$
C: dot capacitance

ΔE = spacing of energy levels

QD conductance – radiation off



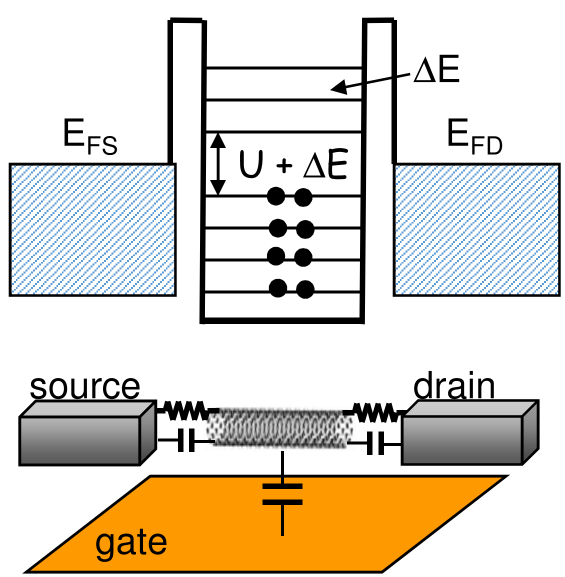




For a review: L. P. Kouwenhoven et al. *Electron Transport in Quantum Dots*, Proc. of the Adv. Study Inst. on Mesoscopic Electron Transport, (Kluwer 1997)

# Carbon Q-dots

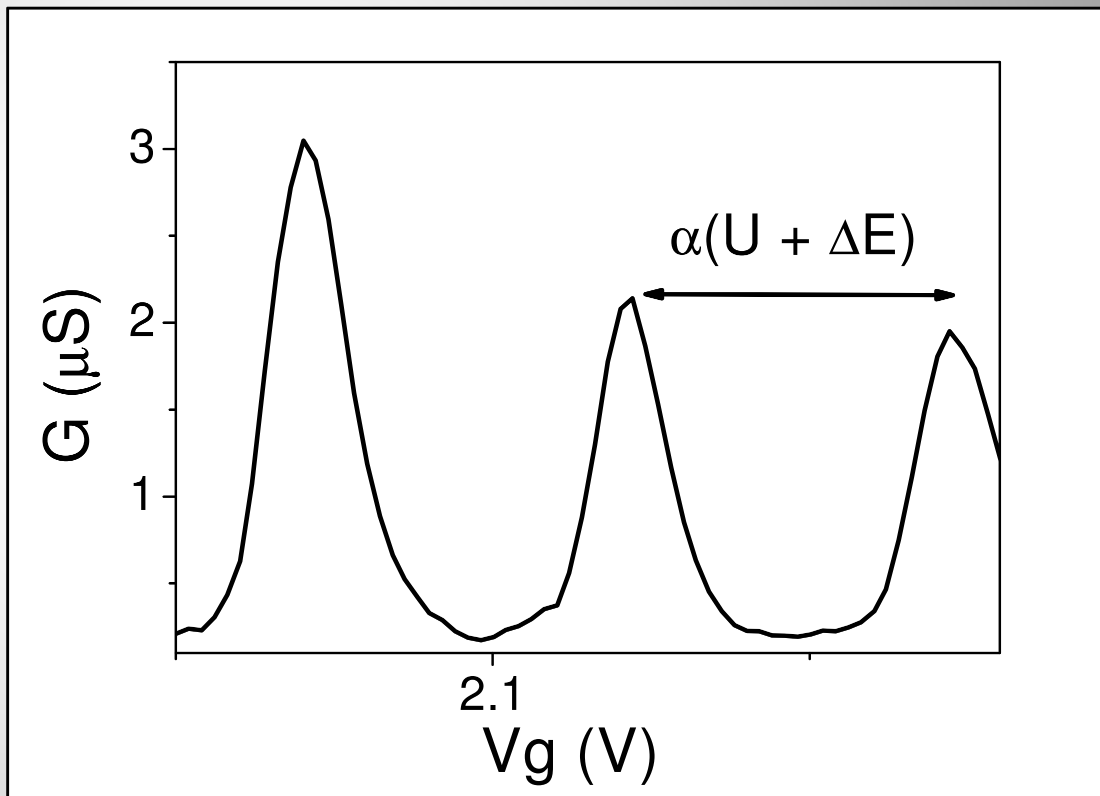
Basic idea:

Change in conductance due to absorption and emission of photons: PAT.



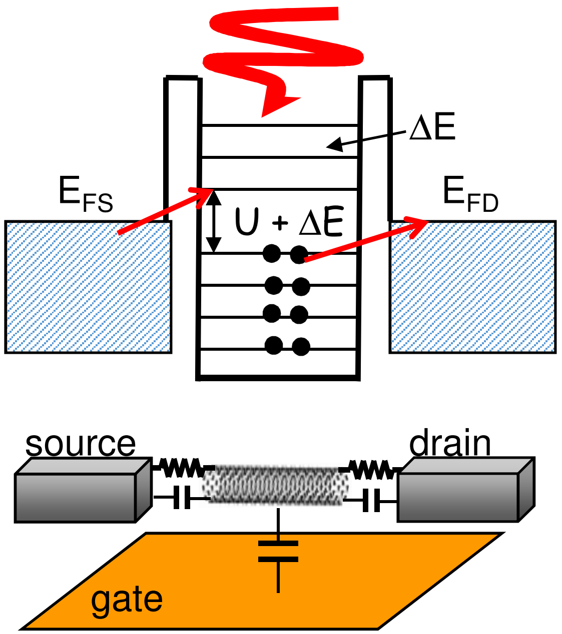

Charging energy: $U = e^2/C$
C: dot capacitance

$\Delta E$ = spacing of energy levels



# Carbon Q-dots

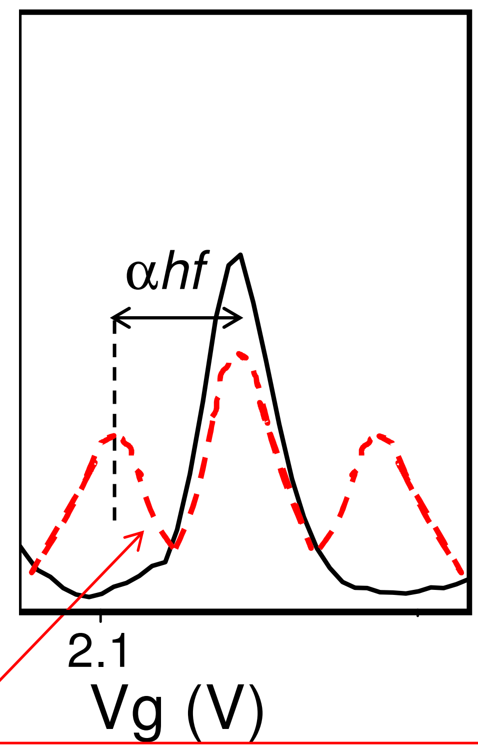
Basic idea:
Change in conductance due to absorption and emission of photons: PAT.




Charging energy: $U = e^2/C$
C: dot capacitance

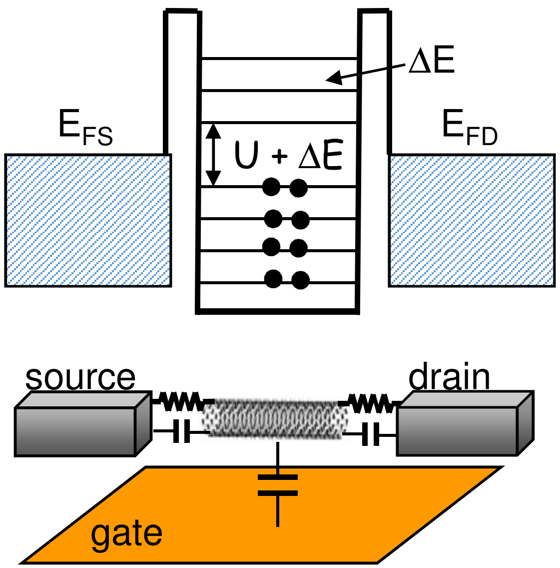
ΔE = spacing of energy levels

QD conductance – radiation ON




D.V. Averin, *et al.*, Phys. Rev. B 43, 6199 (1991).
P. K. Tien and J. P. Gordon, Phys. Rev. 129, 647 (1963).

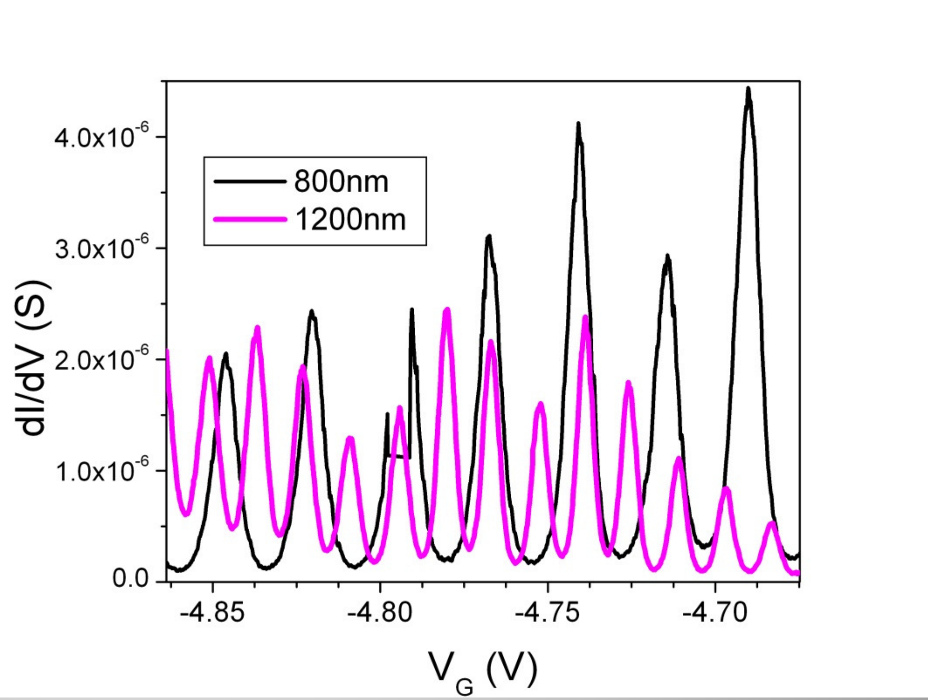
# Why carbon quantum dots for THz detection




U =charging energy
ΔE ~ 1.67 meV for L=1μm

**For L < 1 μm,**
**U + ΔE ~ 10 meV (2.4 THz)!!**

Main advantages:
- U+ΔE larger than in 2DEG quantum dots
- U+ΔE larger than typical Δ in SIS junctions
- U+ΔE inversely proportional to L

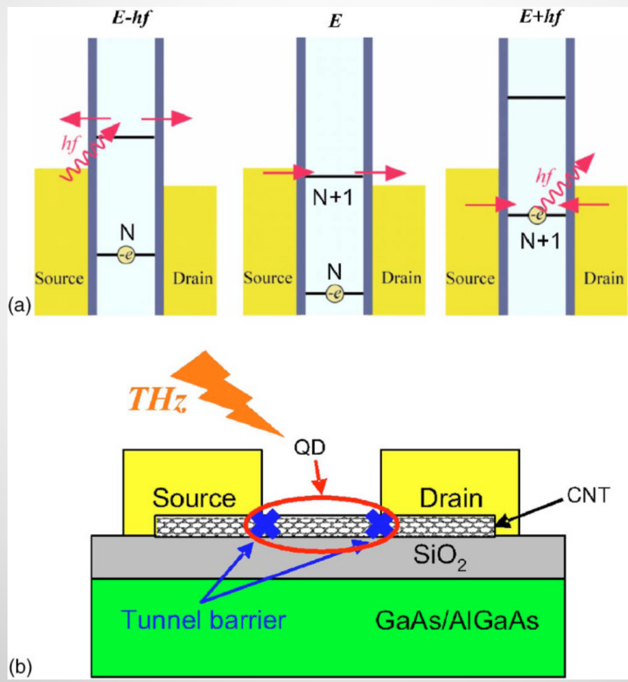


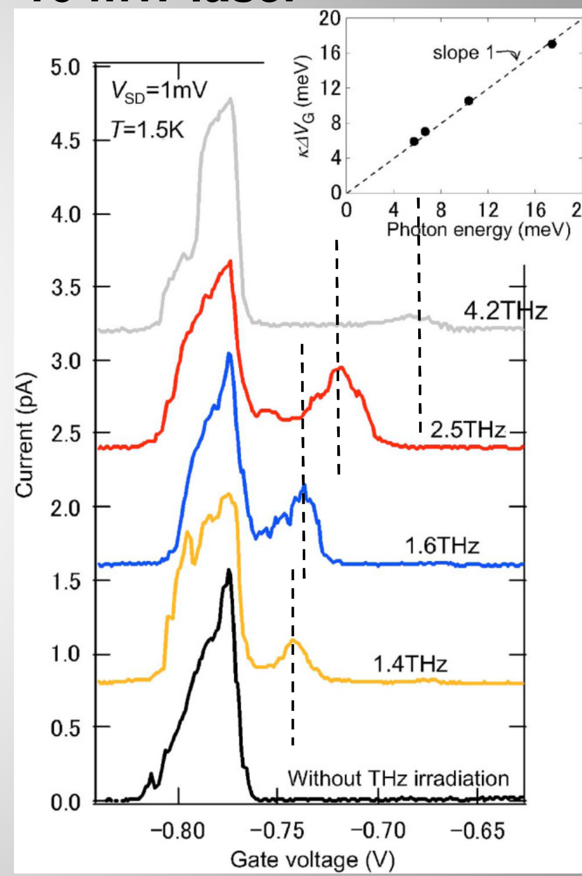
# CNTs and THz detection by PAT

PAT detection demonstrated by
I. Kawano et al. (2008)!

**10 mW laser**

Problems:
- Detected signal weak
- Response from very few samples




I. Kawano et al., J. of Appl. Phys. **103**, 034307 (2008)

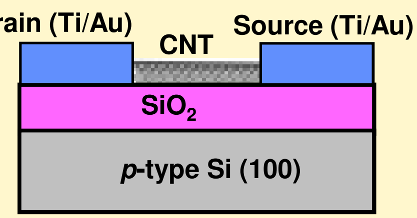
# THz detection by PAT: Our approach

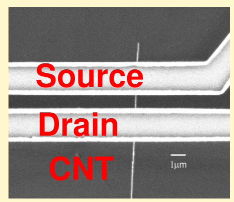
Main challenge:

Coupling THz radiation to quantum dots.

Typical Design:

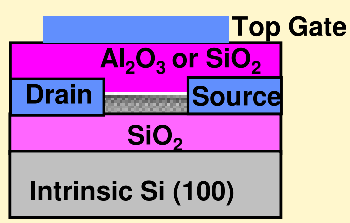
Bottom gate and No THz Antenna → **poor coupling**




New Design :

- Side or Top gate
- Broadband THz Antenna

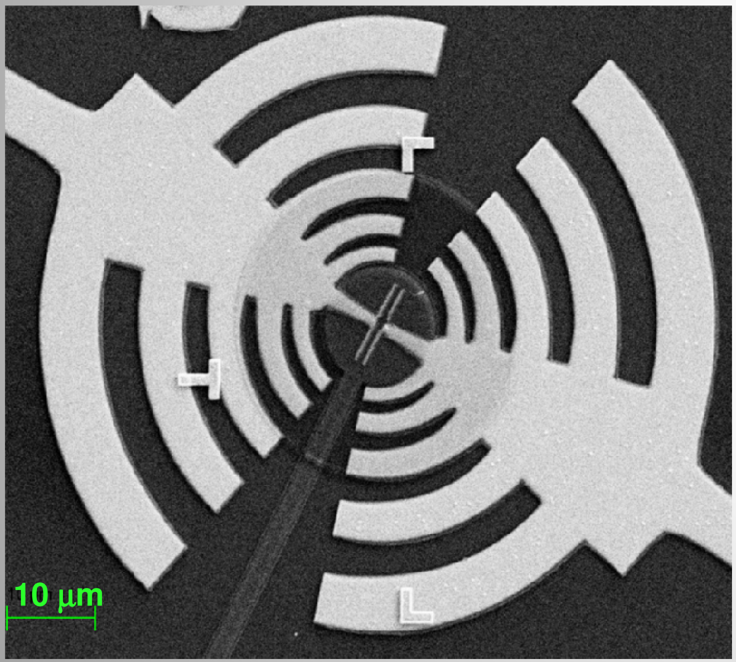



Better coupling:

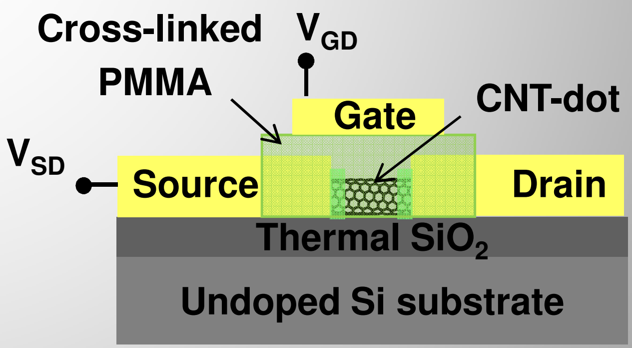
- Impedance mismatch reduced
- larger detection area

# New design: on-chip antenna

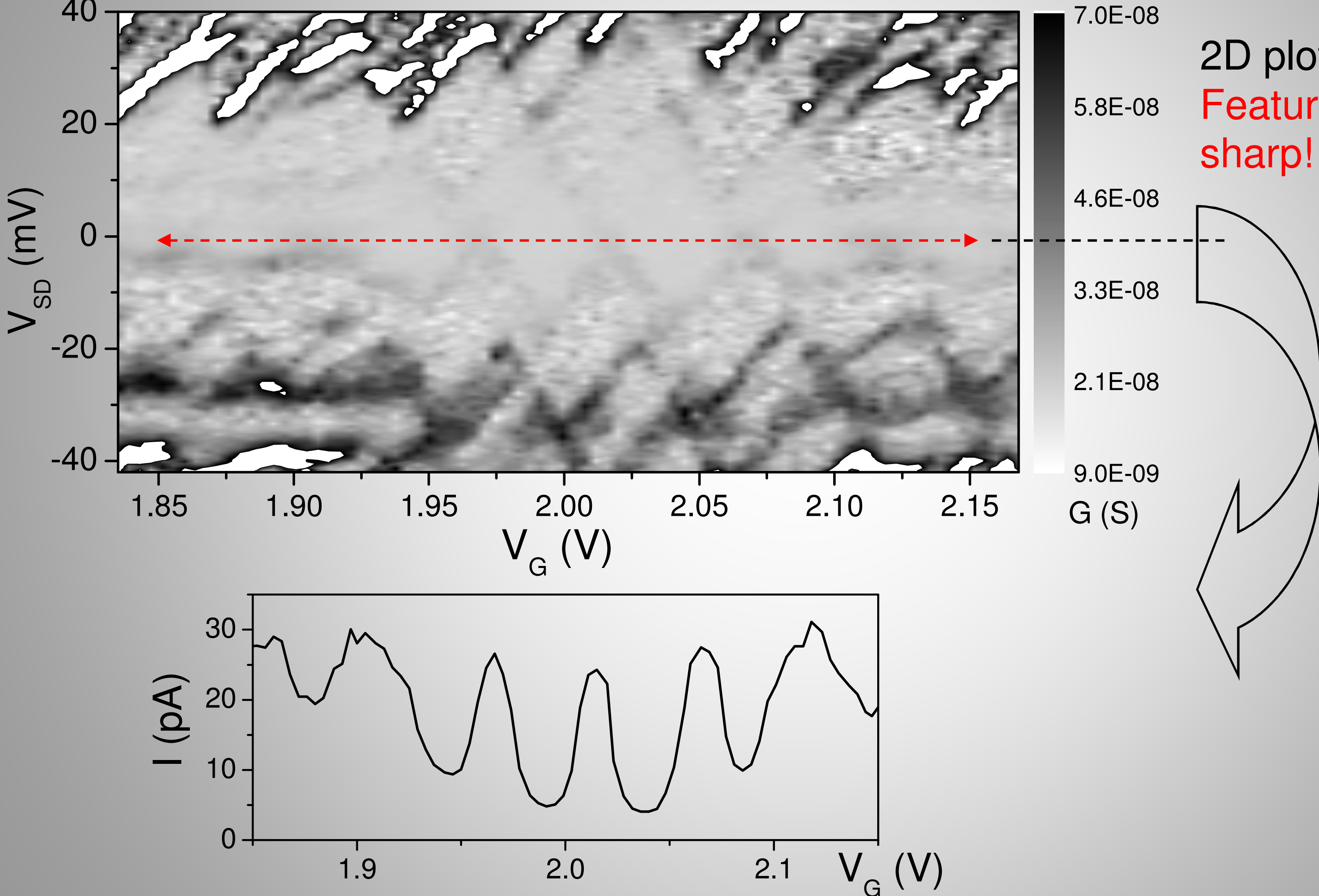
Log-periodic antenna for broad band reception: 700 GHz to 2.5 THz




New design:
- Source-drain electrodes shaped like antennas
- Substrate: intrinsic silicon
- Patterning of small gate electrodes

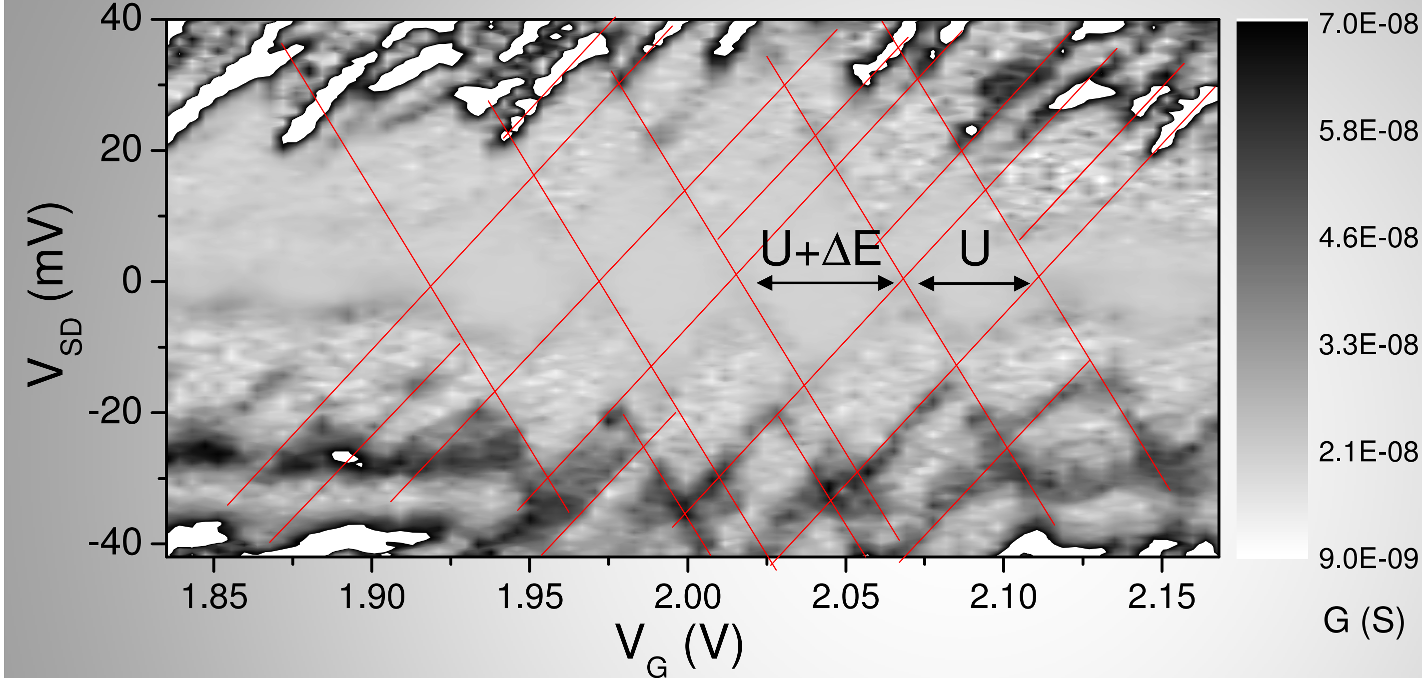


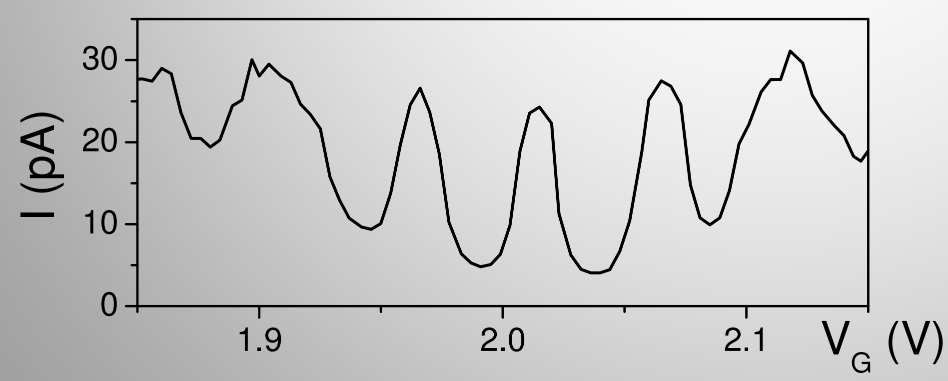
# CNT quantum dot with top gate
# Device A




2D plot:
Features not very sharp!

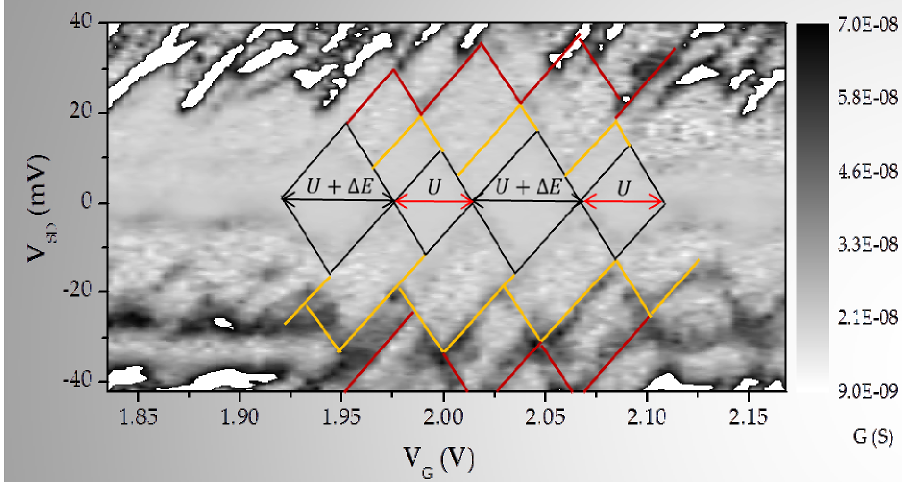
# CNT quantum dot with top gate
# Device A



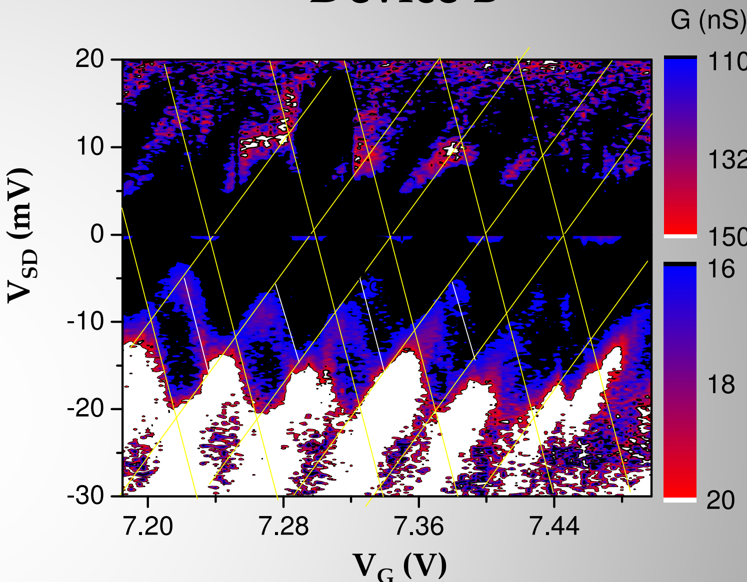
# Characteristic parameters

**Device A**




| Gate efficiency = 32% | |
|---|---|
| Energy (meV) | Capacitance (aF) |
| U = 13.7 | $C_{Dot}$ = 11.7 |
| ΔE = 3.3 | $C_{Source}$ = 3.7 |
| U + ΔE = 17 | $C_{Drain}$ = 4.4 |

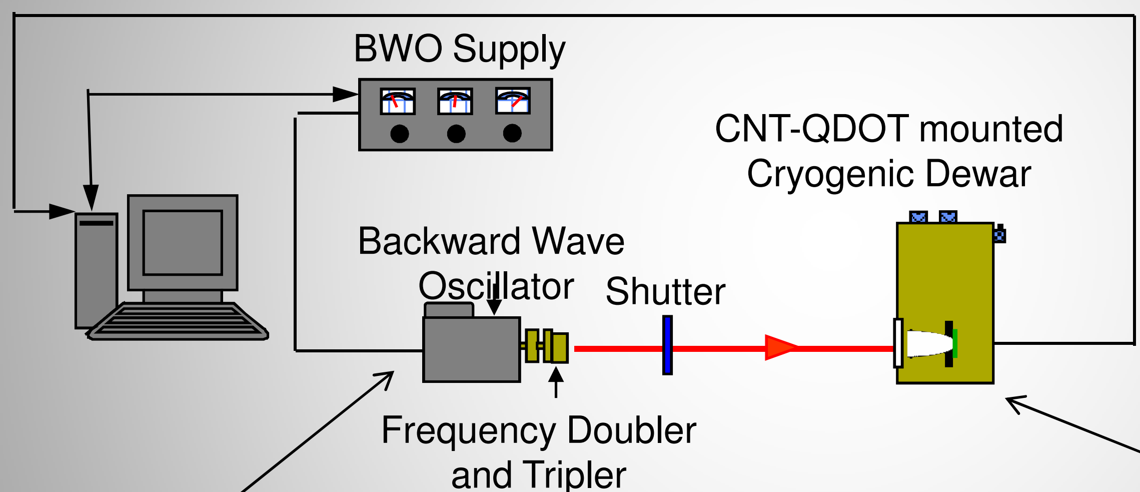
**Device B**



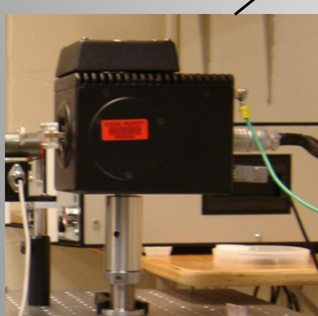

| Gate efficiency = 18% | |
|---|---|
| Energy (meV) | Capacitance (aF) |
| U = 7.4 | $C_{Dot}$ = 21.7 |
| ΔE = 1.9 | $C_{Source}$ = 11.8 |
| U + ΔE = 17 | $C_{Drain}$ = 6.1 |

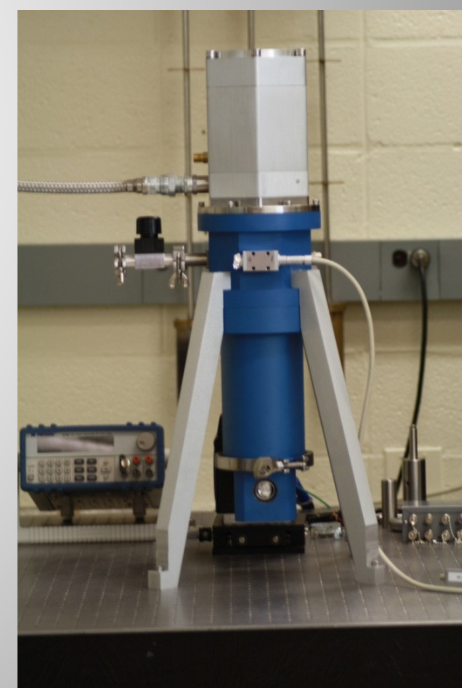
# Experimental set-up

Sample cooled down to about 4K




**Closed-cycle optical cryostat**

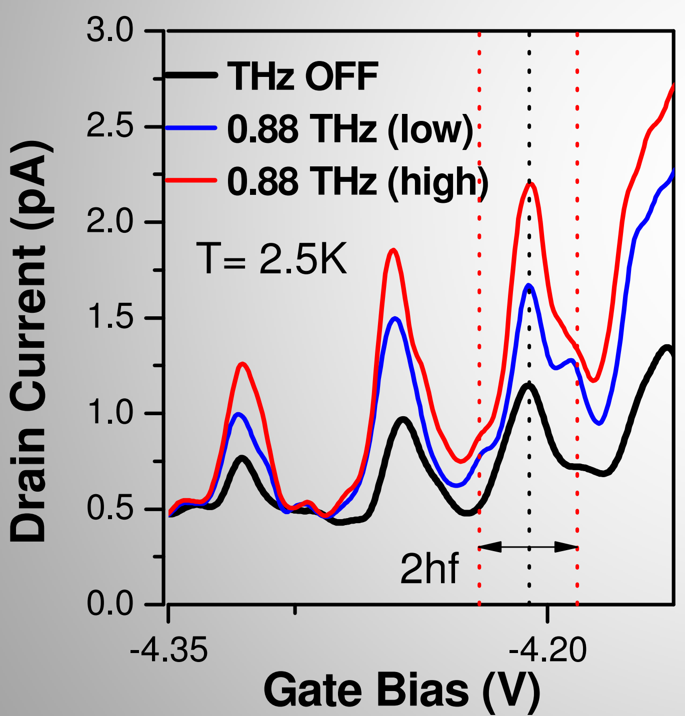




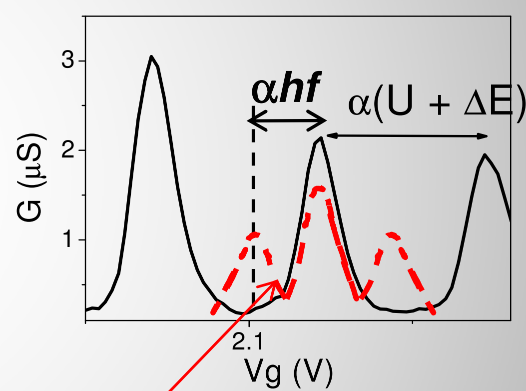
**Tunable BWO: 0.6 – 1THz (0.1 - 0.02 mW)**

# Device B: BWO response and T dependence

## Measured THz response



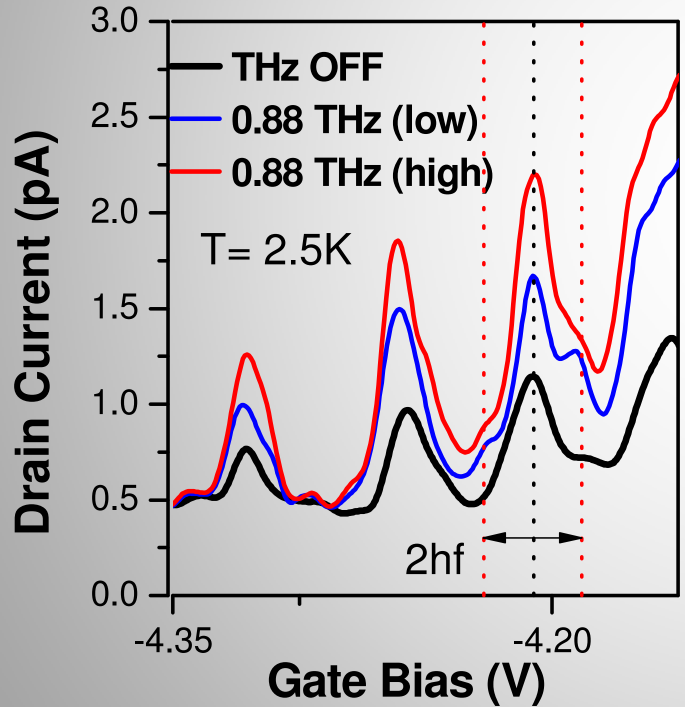

## Expected THz response




D.V. Averin, *et al.*, Phys. Rev. B 43, 6199 (1991).
P. K. Tien and J. P. Gordon, Phys. Rev. 129, 647 (1963).

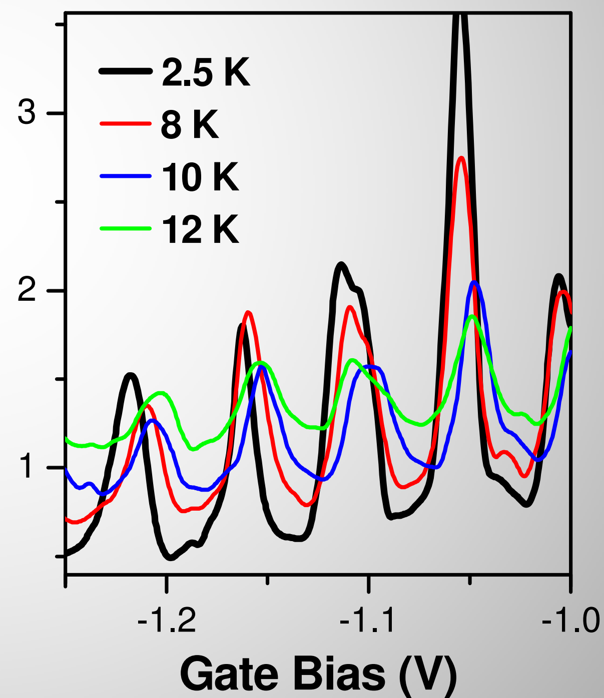
# Device B: BWO response and T dependence

## Measured THz response

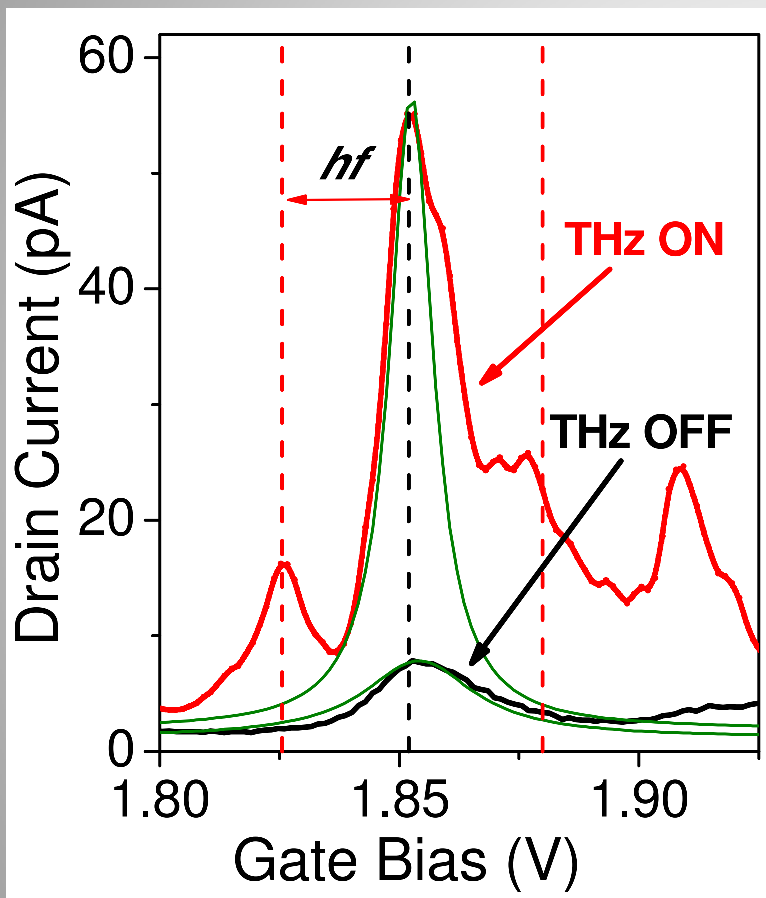


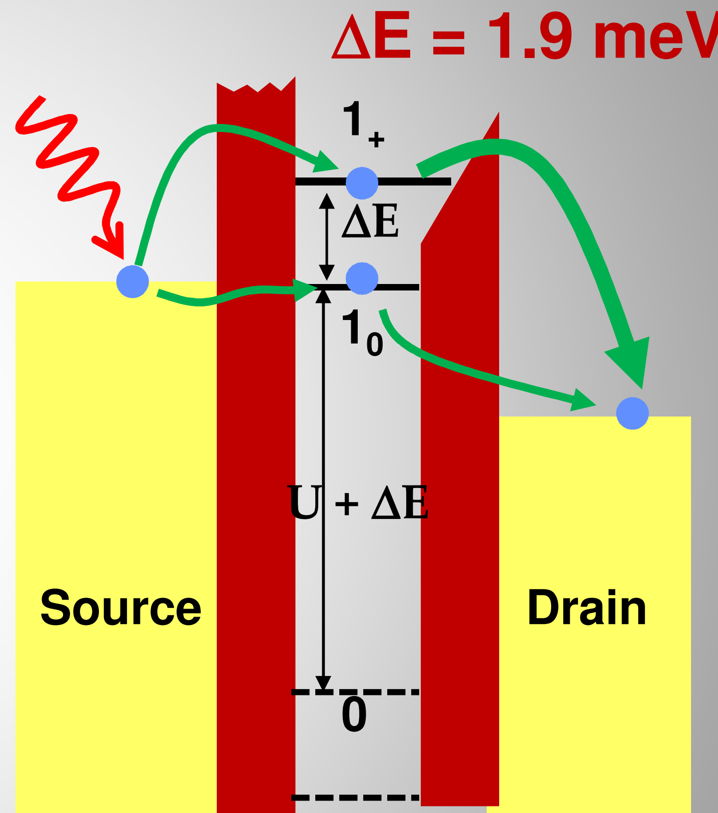

## Temperature dependence

## No THz applied



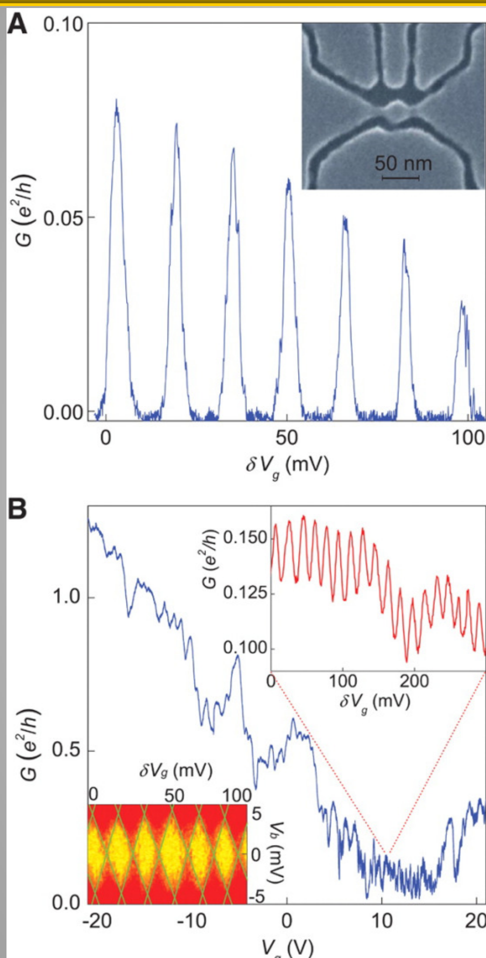
# Device B: 1.3 THz response
# (1 mW laser source at UMD)



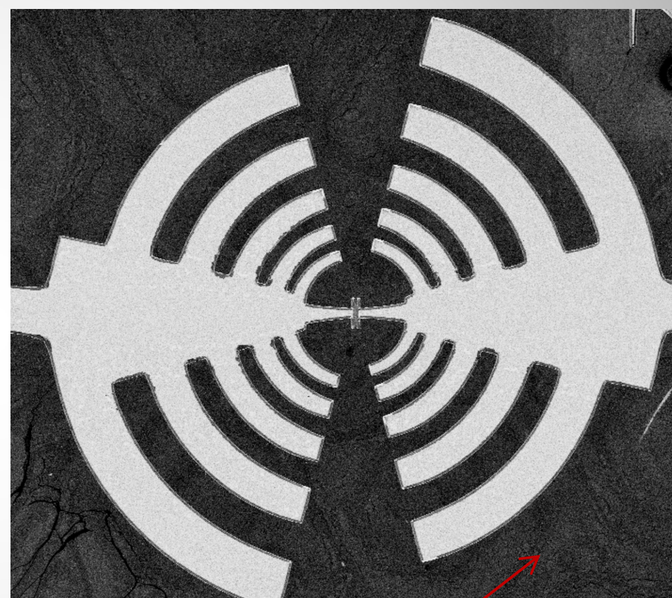

**Non-equilibrium cooling of electrons in the CNT-Dot when THz frequency exceeds ΔE**

# Graphene QDots




L. A. Ponomarenko et al., Science 320, 5874 (2008)

**Our approach**



**Graphene on SiC from K. Gaskill's group**

# Summary

**PAT in CNT quantum dots with on-chip antennas:**

- **Broadband detection in the range 0.6 THz - 1.3 THz**
- **High sensitivity (NEP $< 10^{-15}$ W/Hz$^{-1/2}$)**
- **Spectral resolution (better than 0.1 THz)**
- **Strong signal at 5K (source power 0.02 – 1 mW)**
- **THz-induced cooling**

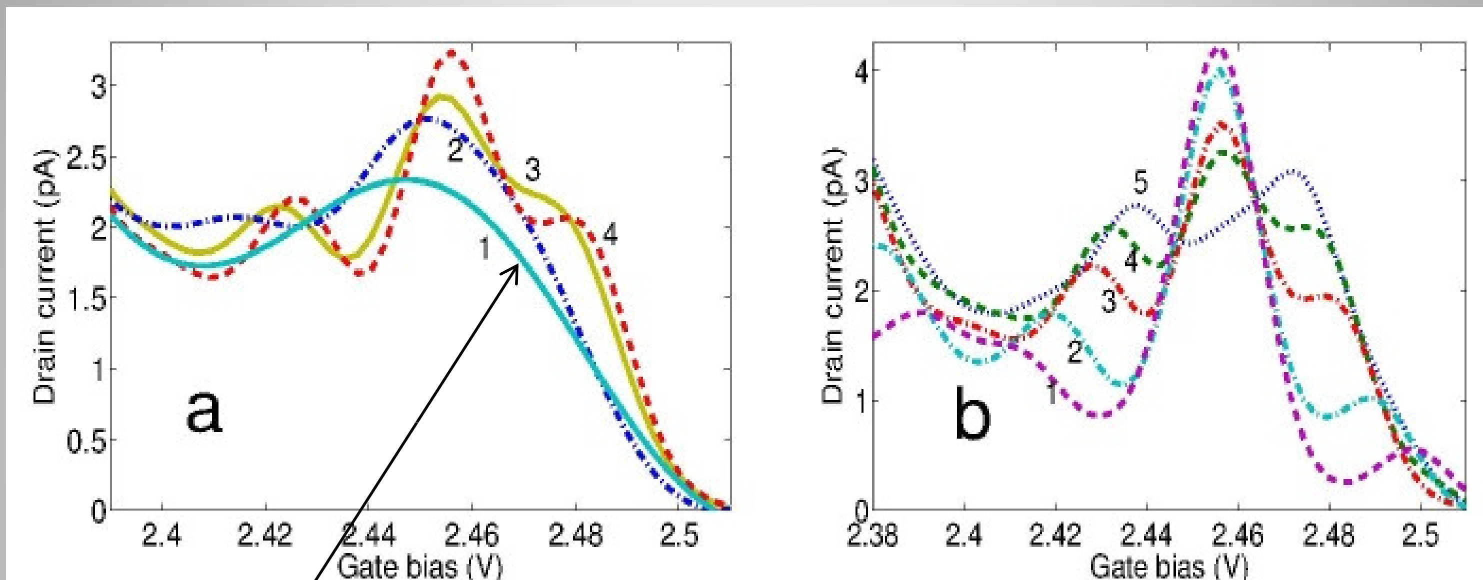
M. Rinzan et al. Nano Letters **12,** 3097 (2012)

**Future and ongoing work:**

- **Better quality quantum dots.**
- **Quantum dots with tunable barriers**
- **Extend process to graphene**

**THANK YOU!**

# Simulations of cooling effect



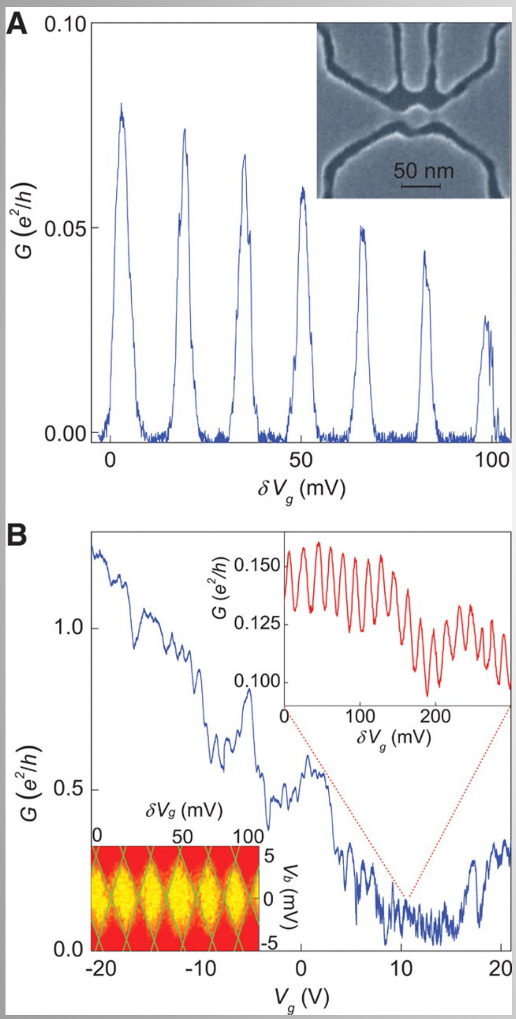

**THz off**

**Fixed frequency (1.26 THz)**

**Increasing field intensity from curve 2 to 4**

**Fixed field intensity.**
**Decreasing frequency from curve 1 to 5.**

# Graphene Q-dots




L. A. Ponomarenko et al., Science **320,** 5874 (2008)

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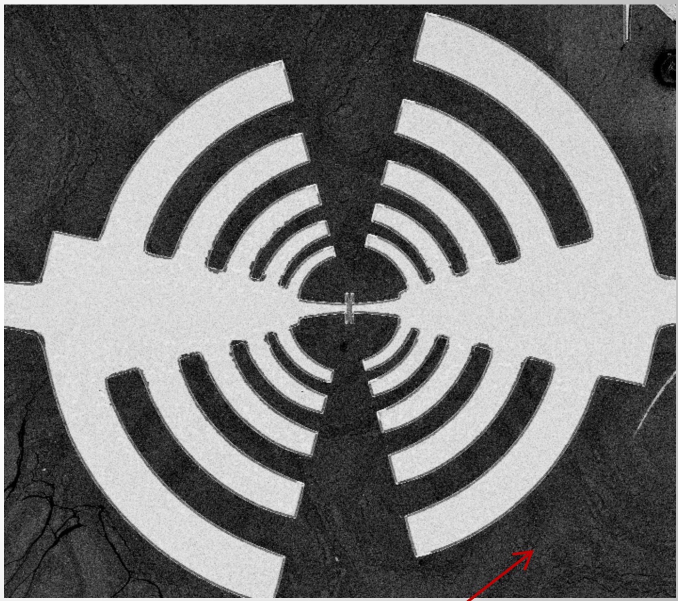
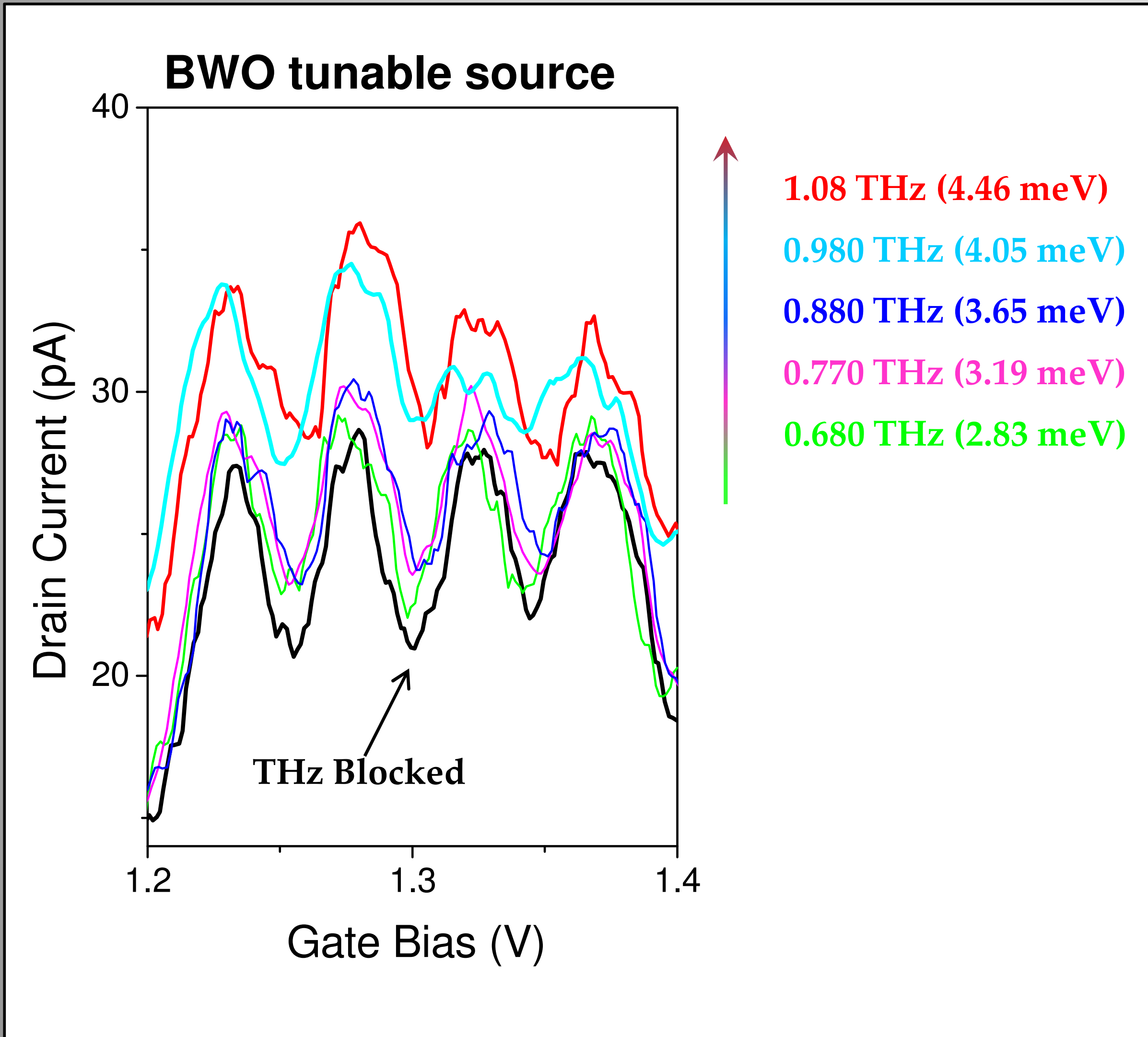


Graphene on SiC from K. Gaskill's group

# Device A : Broad band response




- No clear PAT peaks
- Main peak enhanced for frequencies above 0.880 THz

**Energy level spacing**

**$\Delta E = 3.3$ meV**

# Non-equilibrium cooling

**Quantum kinetic equation for non-equilibrium distribution function $g_n$ , the PASET current and the electron-phonon recombination**

$$\frac{\partial g_n(\varepsilon_k)}{\partial t} = I_T(g_n, \varepsilon_k) + I_{\text{ep}}(g_n, \varepsilon_k) \equiv 0$$

$$I_T(g_n, \varepsilon_k) = \sum_m J_m^2(\alpha_{\text{S,D}}) \left\{ \left[ \varpi_{k,+}^{\text{S}}(n,m) - \varpi_{k,-}^{\text{S}}(n,m) \right] - \left[ \varpi_{k,+}^{\text{D}}(n,m) - \varpi_{k,-}^{\text{D}}(n,m) \right] \right\}$$

$$I_{\text{ep}}(g_n, \varepsilon_k) = -\frac{g_n(\varepsilon_k) - g_n^{(0)}(\varepsilon_k)}{\tau_{ep}}$$

$$\alpha_{\text{S,D}} = e\tilde{V}_{\text{S,D}}/hf$$

$$\varpi_{k,+}^{\text{S(D)}}(n,m) = \Gamma_{\text{S(D)}}(\varepsilon_+^{S(D),m})\text{f}(\varepsilon_+^{S(D),m}, T_{\text{bath}})\left[1 - g_n(\varepsilon_k)\right]$$

$$\varpi_{k,-}^{\text{S(D)}}(n,m) = \Gamma_{\text{S(D)}}(\varepsilon_-^{S(D),m})\left[1 - \text{f}(\varepsilon_-^{S(D),m}, T_{\text{bath}})\right] g_n(\varepsilon_k)$$

$$\varepsilon_{+(-)}^{S(D)} = \varepsilon_k + \Delta E \cdot l + E_{\text{G}} + \Delta U_{n(n-1)}^{\text{S(D)}} + mhf$$

# Non-equilibrium cooling

**Power balance equation:**

$$W_T + W_{\mathrm{ep}} \equiv 0$$

**With the power PASET tunneling power:**

$$W_T = \sum_k \varepsilon_k I_T \{g_n, \varepsilon_k\}$$

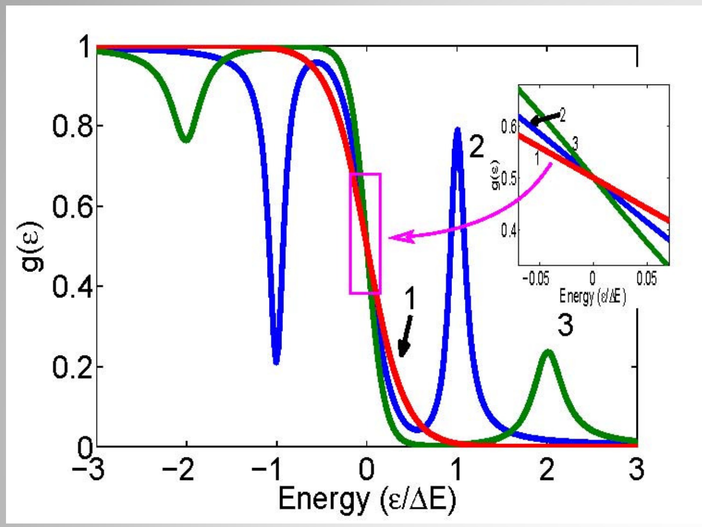
**And the power dissipated due to electron-phonon collision:**

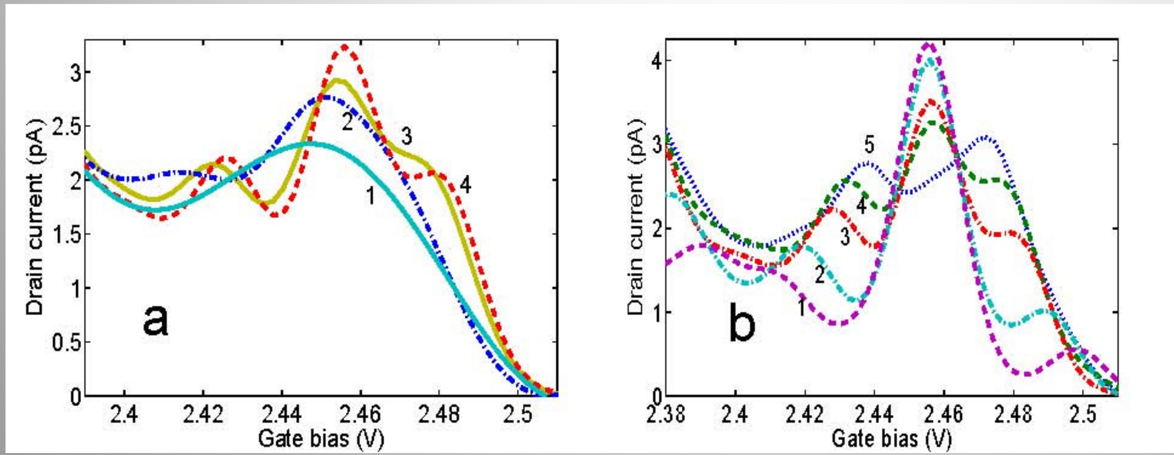
$$W_{\mathrm{ep}} = \sum_k \varepsilon_k I_{\mathrm{ep}} \{g_n, \varepsilon_k\}$$

**With the number of electrons in the dot given by:**

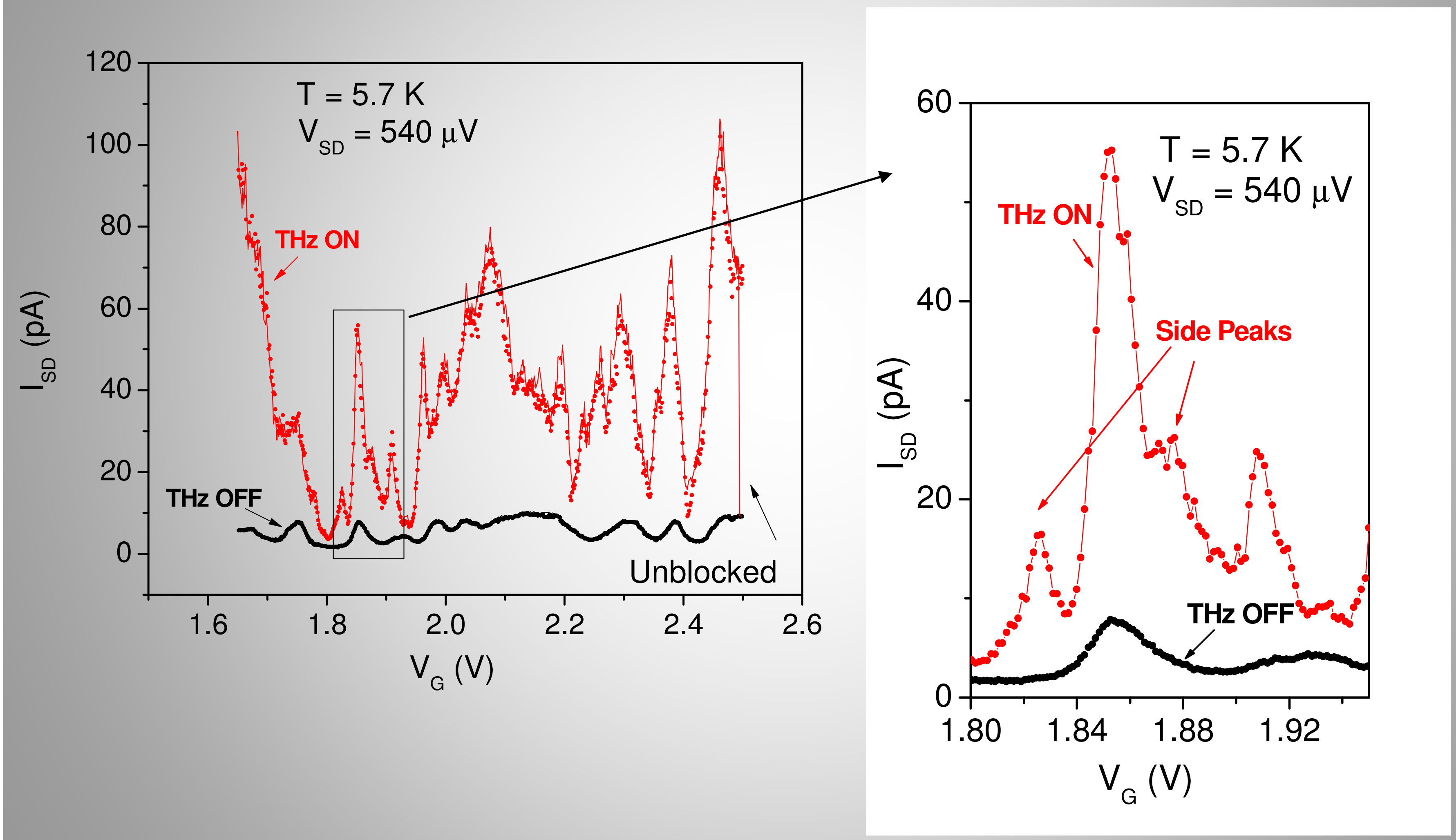
$$n = \sum_k g_n(\varepsilon_k)$$

# Non-equilibrium cooling

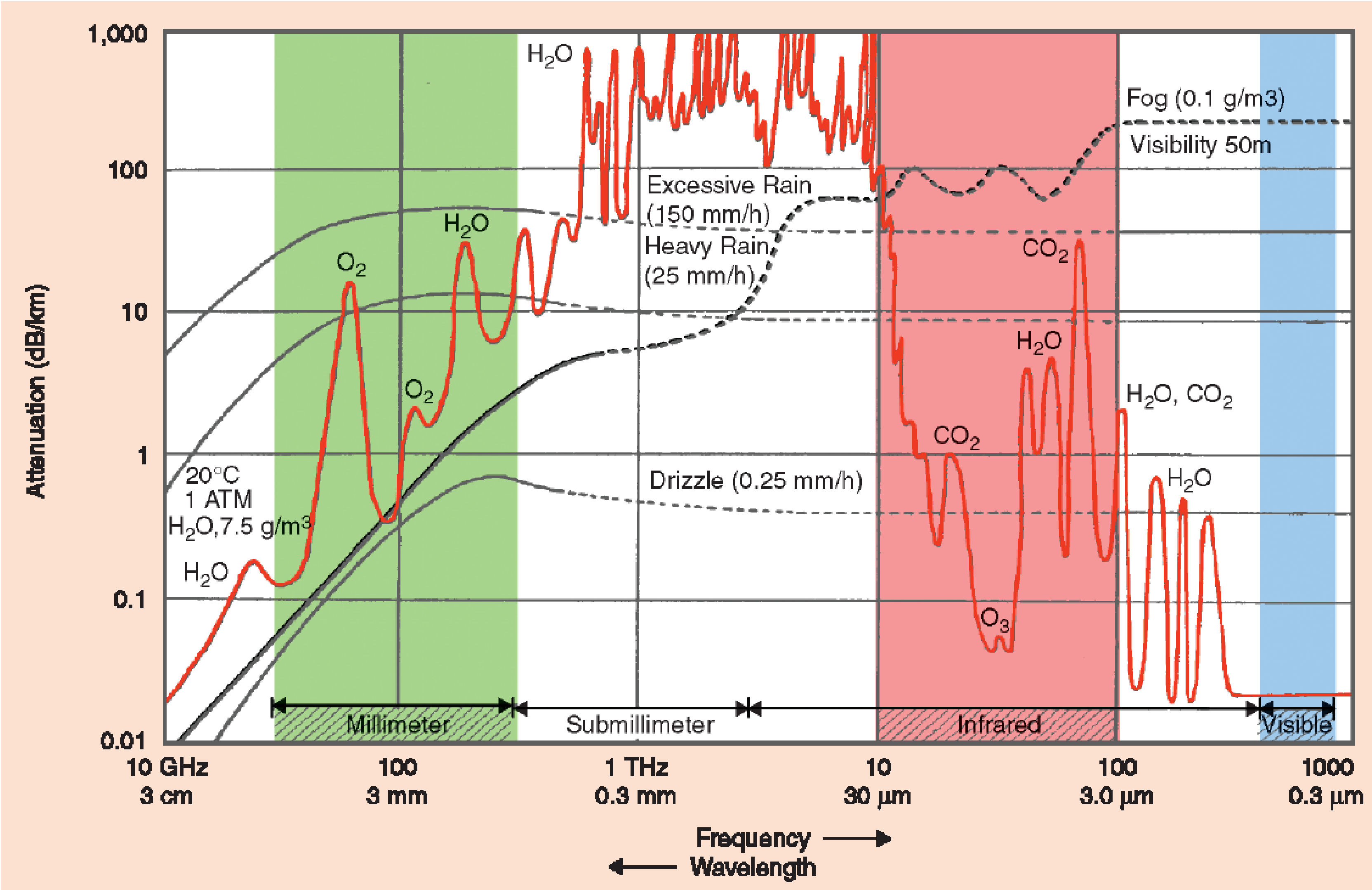


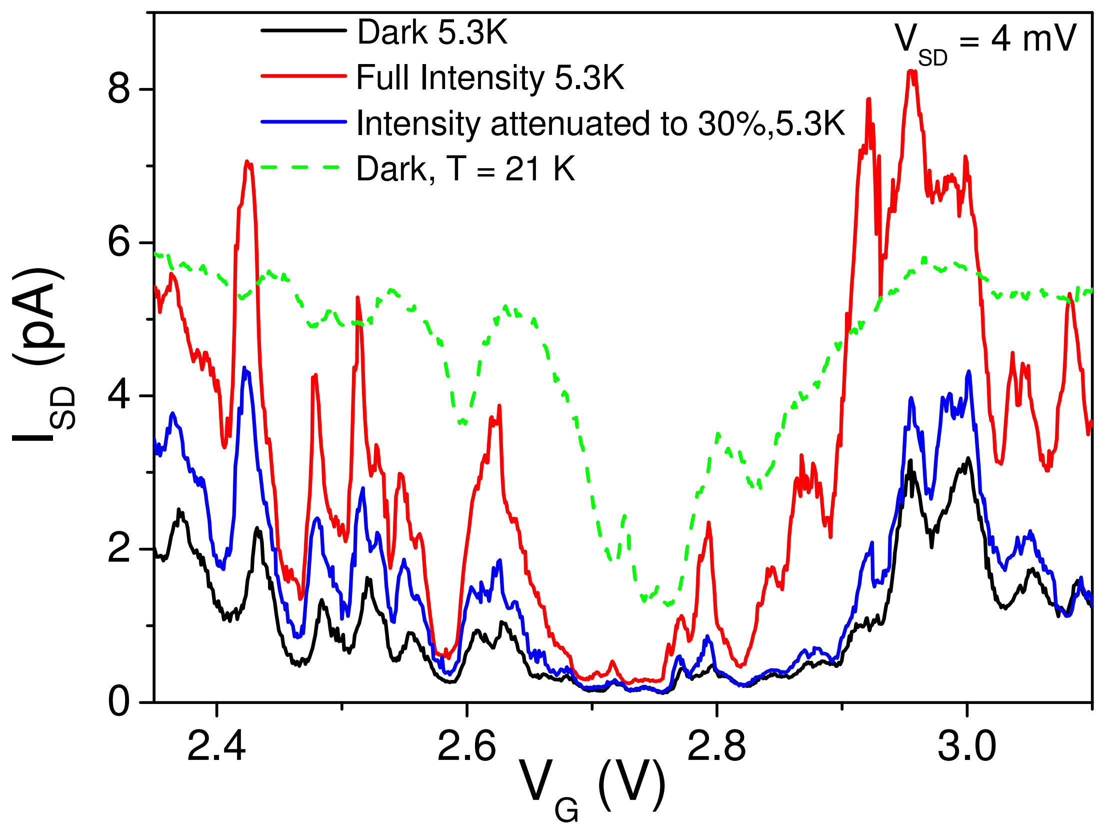
# Laser source 1.3 THz: Device B



# THz attenuation spectrum

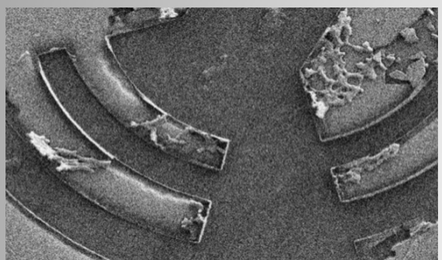


# Laser source 1.31THz: Device A

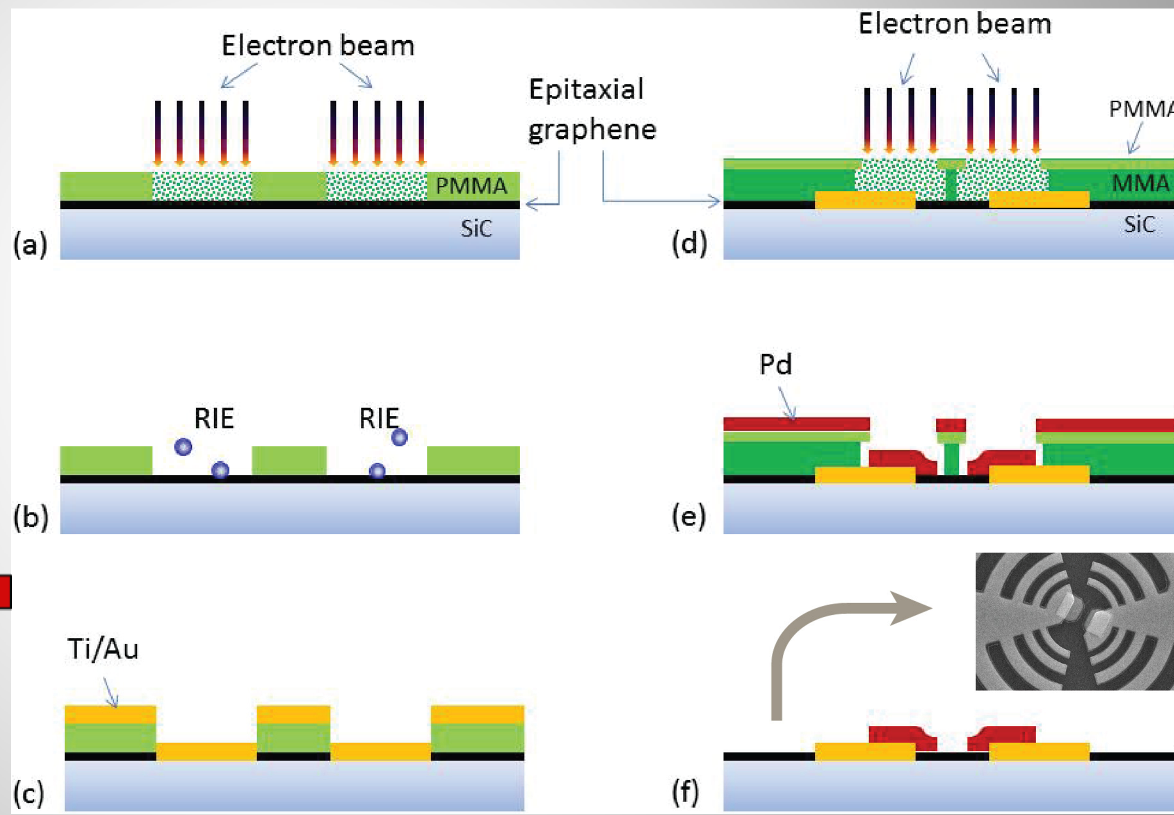


# Development of detector arrays

**Adhesion problems for graphene on SiC**



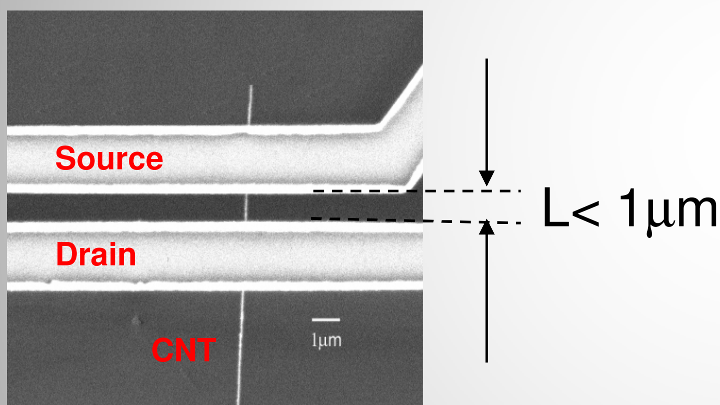
**Fabrication process for q-dot graphene detectors**

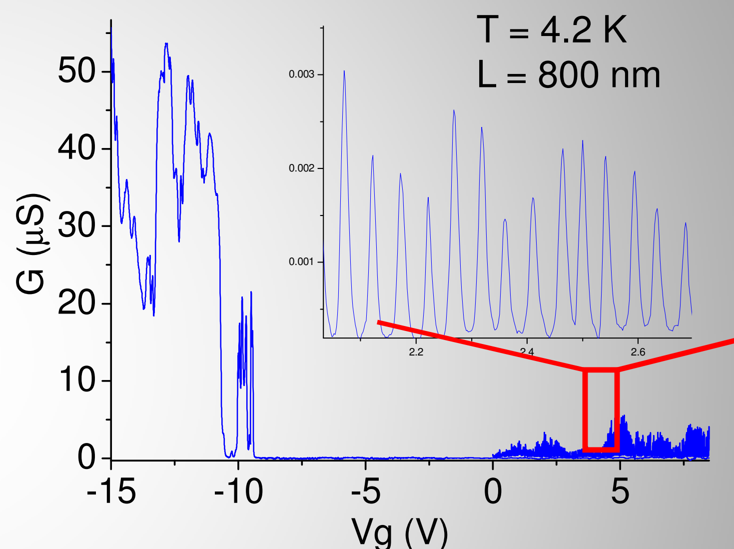


# Quantum dot for semiconducting CNTs

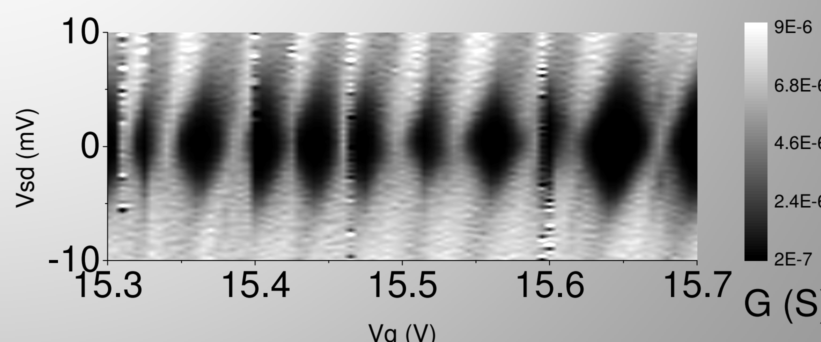
Quantum dots:
Two main ingredients

1)

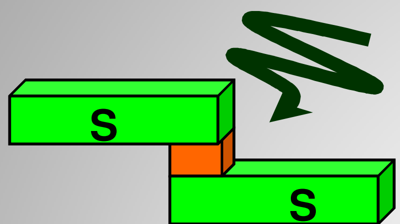


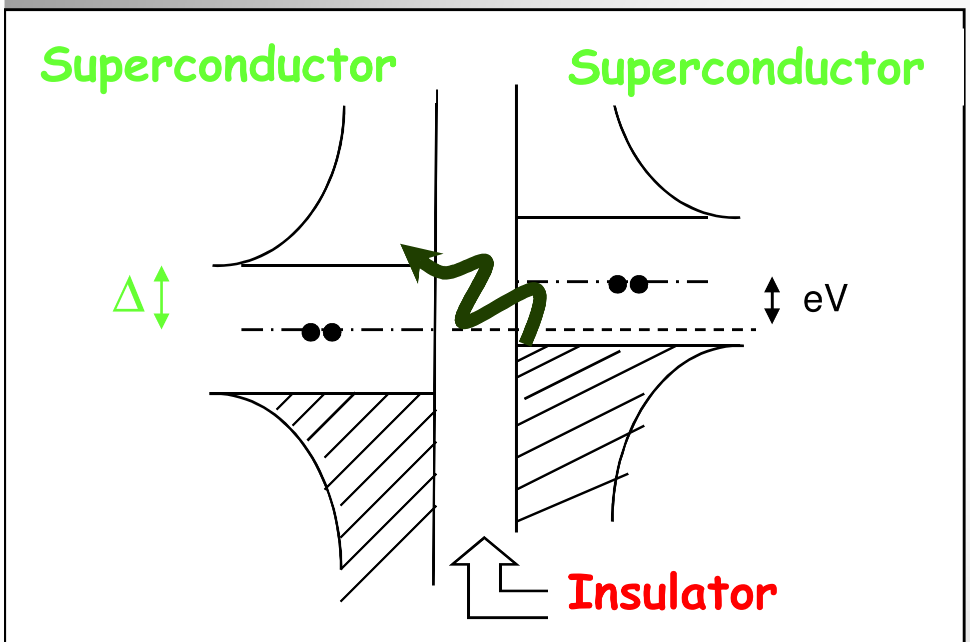




2) Electrode material:
Ti, Al for large contact barriers

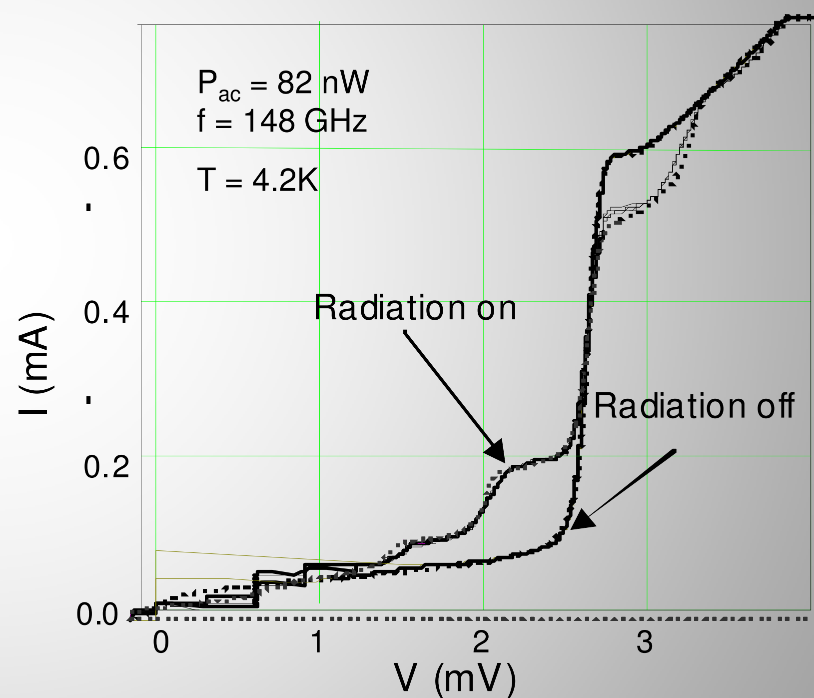


# PAT in superconducting detectors



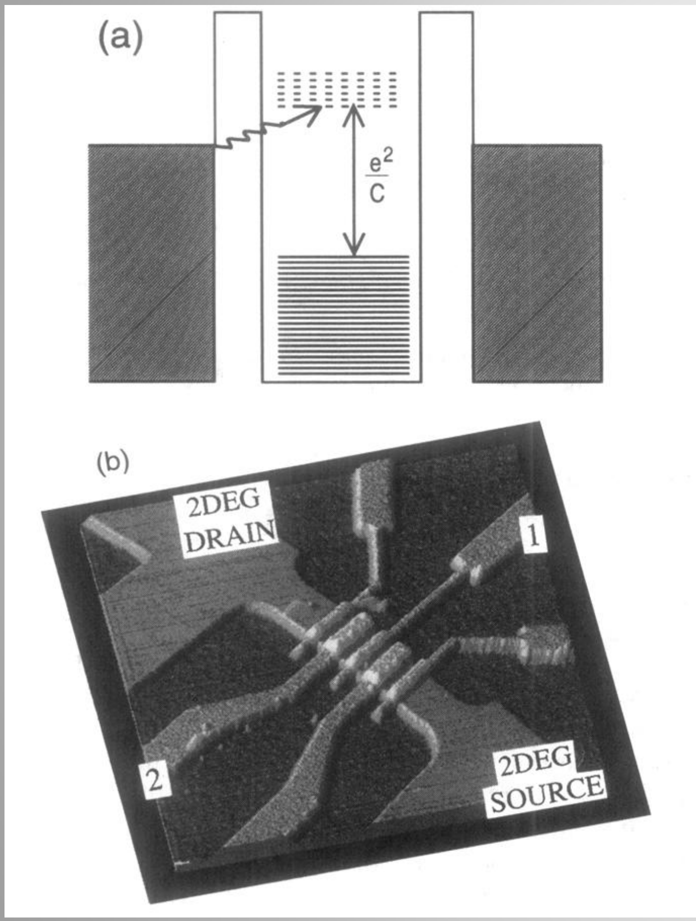




Photon assisted tunneling:
Widely used in SIS detectors




P. K. Tien and J. P. Gordon, Phys. Rev. 129, 647 (1963).

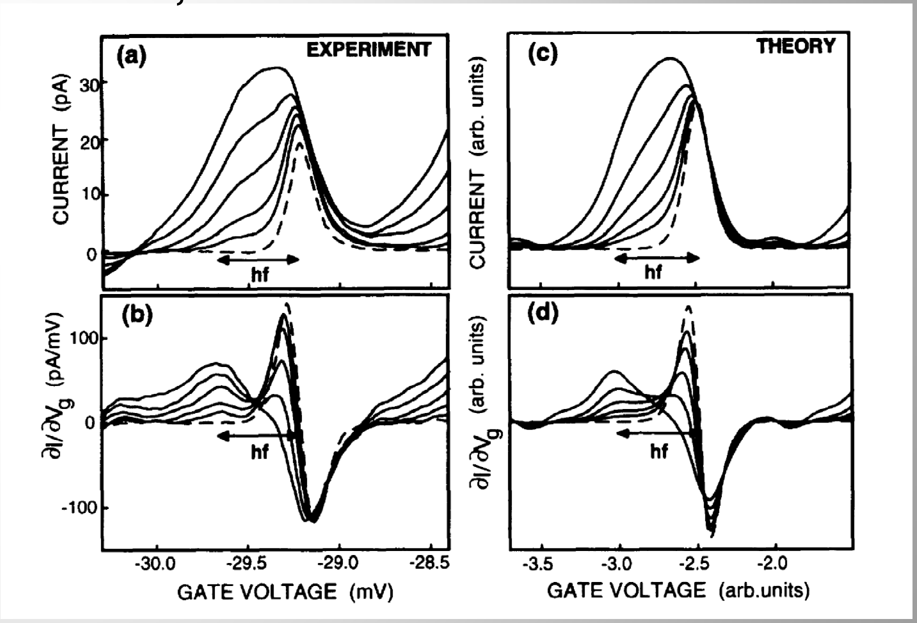
# PAT in quantum dots




Photon assisted tunneling:

For quantum dots first observed in 2DEG, Kouwenhoven et al., 1994

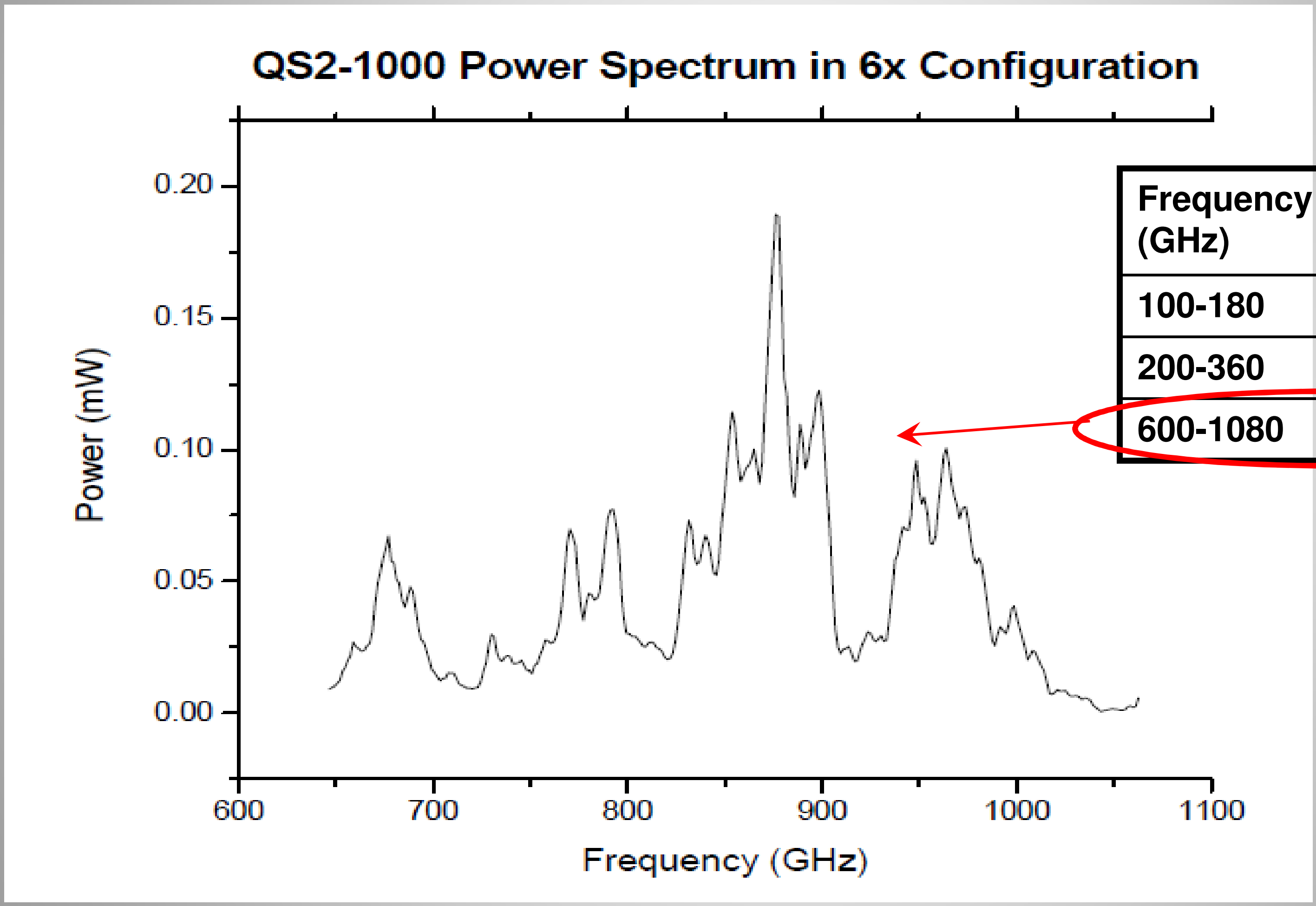
**9-36GHz, T = 100mK**




D.V. Averin, A. N. Korotkov and K. K. Likharev, Phys. Rev. B **43**, 6199 (1991).

P. K. Tien and J. P. Gordon, Phys. Rev. **129**, 647 (1963).

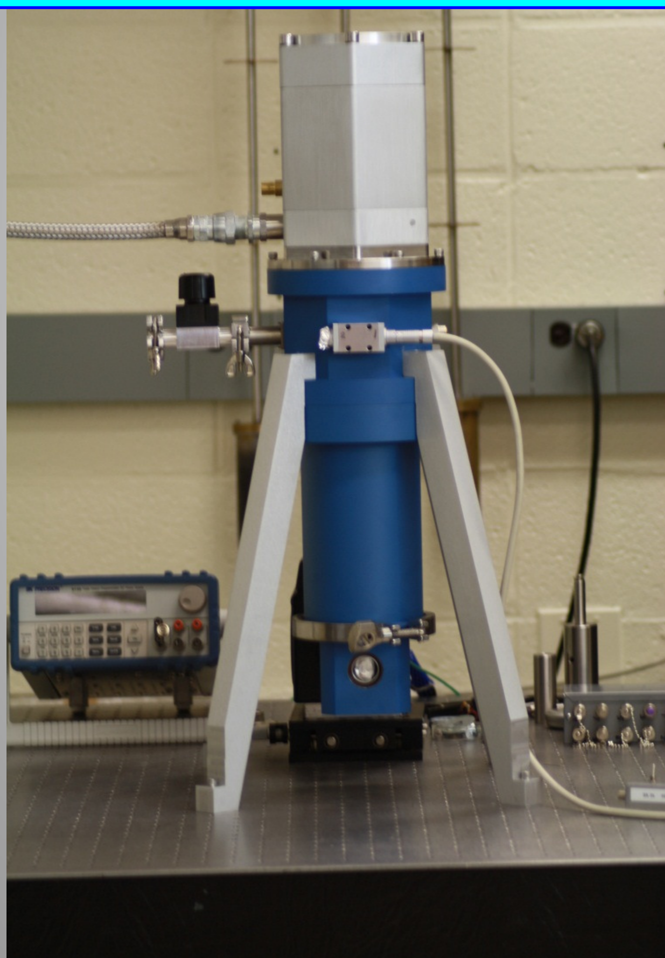
# BWO source



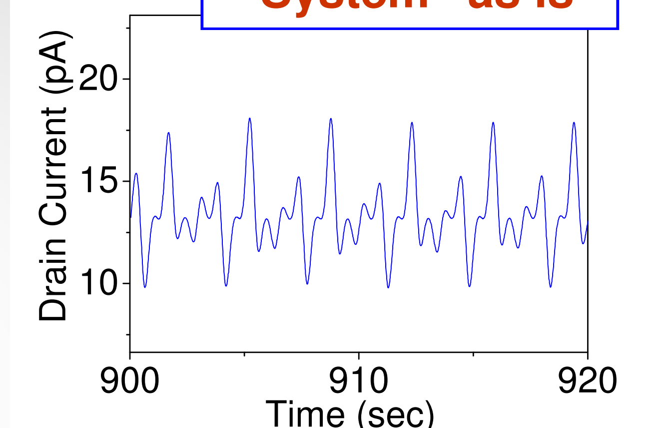

| Frequency (GHz) | Power (mW) |
|---|---|
| 100-180 | 10-100 |
| 200-360 | 1-10 |
| 600-1080 | .02-0.1 |

# Cryo-free system

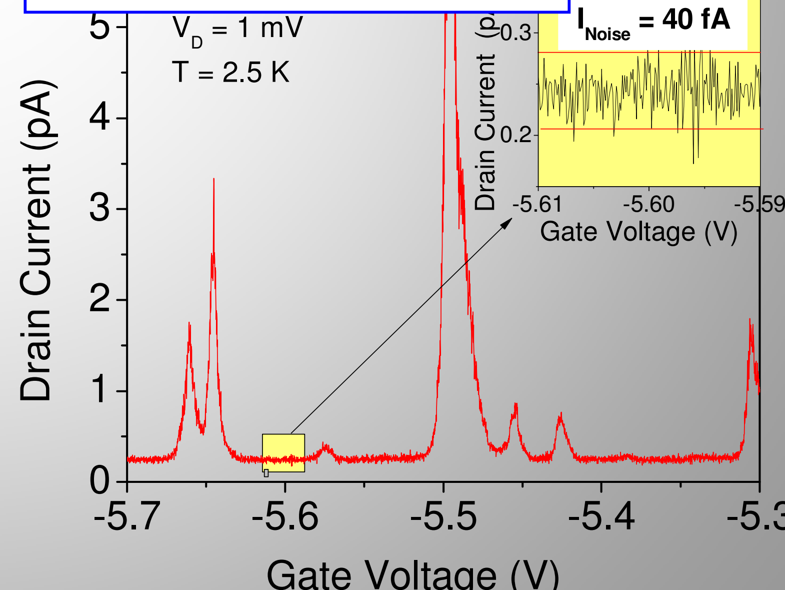
**Improving noise level of a commercial close cycle cryostat for quantum dot spectrometer measurements.**



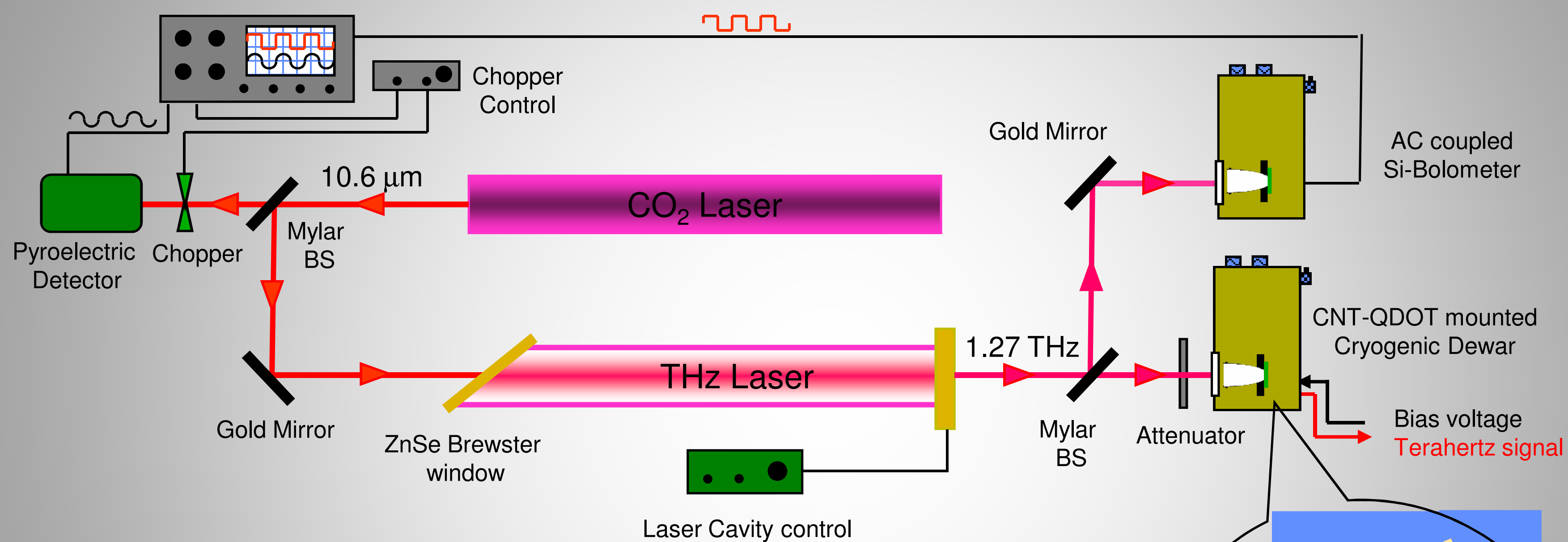
**System “as is”**

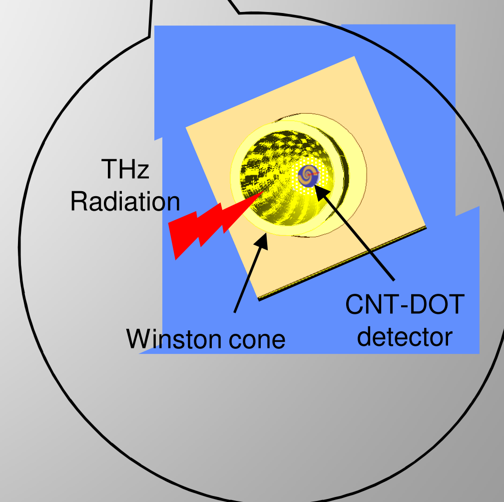



**After improvements**



# THz laser source @ UMD



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