# Towards a Solid State Terahertz Oscillator: Bloch Oscillation in an Electrical Biased Superlattice

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Mayo Foundation

Funded by: **DARPA/ONR**

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*Institute for*
*Quantum Engineering, Science and Technology*

Center for Terahertz Science and Technology
UC Santa Barbara
http://www.qi.ucsb.edu/

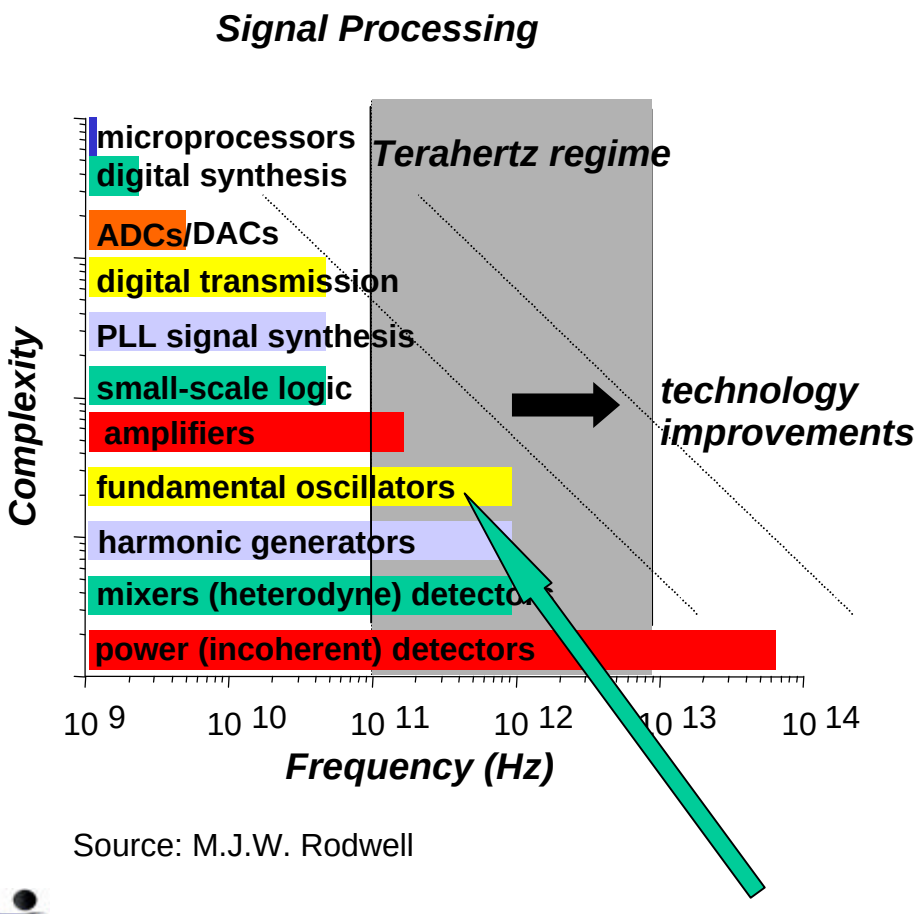
# Agenda

- **Perspective**
- **Concept**
- **Bloch oscillators and Stark Ladders**
  - **Critical issues**
    - **Domains**
    - **Contact resistance**
- **Ground work**
  - **GaAs/AlGaAs**
  - **InGaAs/AlAs**
- **InAs/AlSb**
  - **Domain stabilization**
  - **Minibandstructure**
  - **Projections**

- **Prognosis**

Perspective:

# Terahertz Electronics ⇒ Photonics




Source: M.J.W. Rodwell

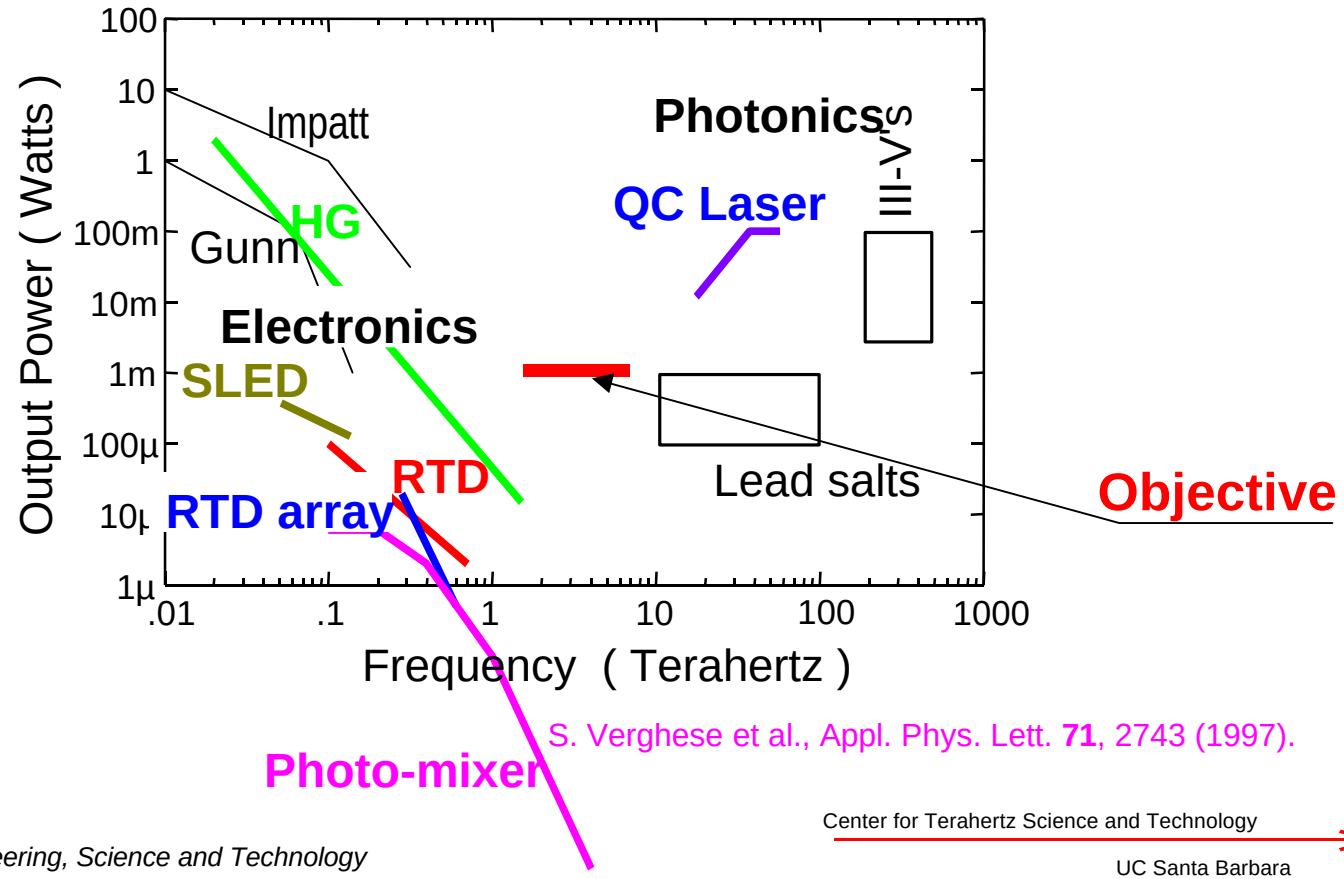
Technology applications

- Information
  - Ultra fast signal processing "Time is money"
  - Massive data transmission
- Space Science
  - Cosmology
  - Planetary, cometary
  - Cosmochemistry
- Environment
  - Atmospheric sensing
- Defense
  - Chemical agent detection
  - Digital radar
  - Imaging radar
  - Covert communication
    - Space-space
    - Short range battle field
- Transportation
  - Collision avoidance
- Material processing
  - Tomography

⇒Unknown applications created by new technology

Perspective:

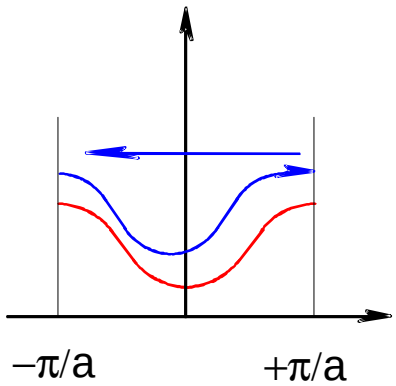
# Terahertz Fundamental Oscillators: "State of the Art" and Objective

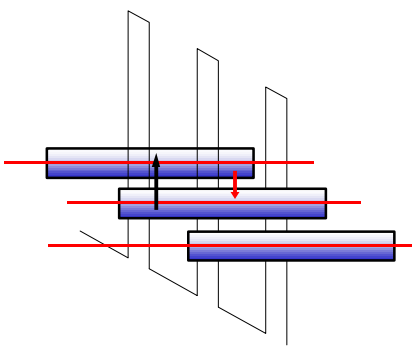


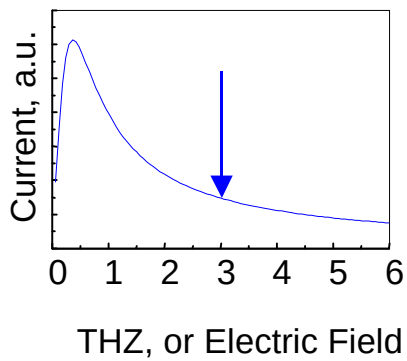

S. Verghese et al., Appl. Phys. Lett. **71**, 2743 (1997).

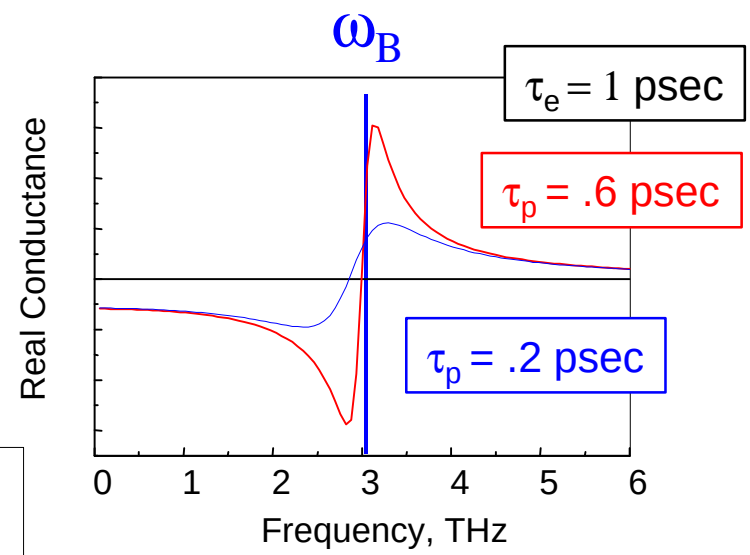
Concept:

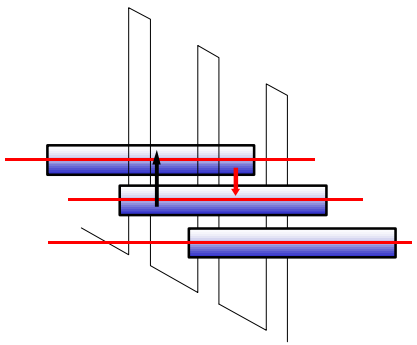
# Terahertz Gain and Loss in a Miniband Superlattice

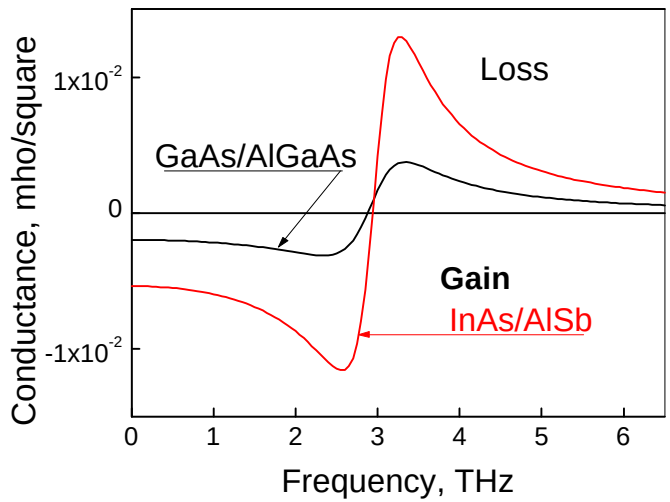









# Agenda

## Science

**Measure THz loss and gain**

## Technology

**THz oscillator**

**AlGaAs/GaAs $\chi$**

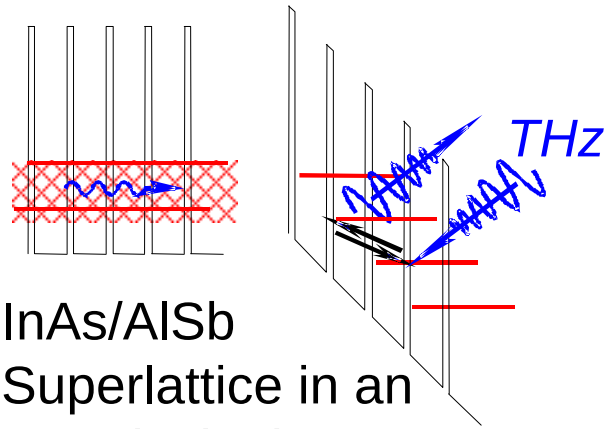
**InGaAs/AlAs $\chi$**

**InAs/AlSb preferred**

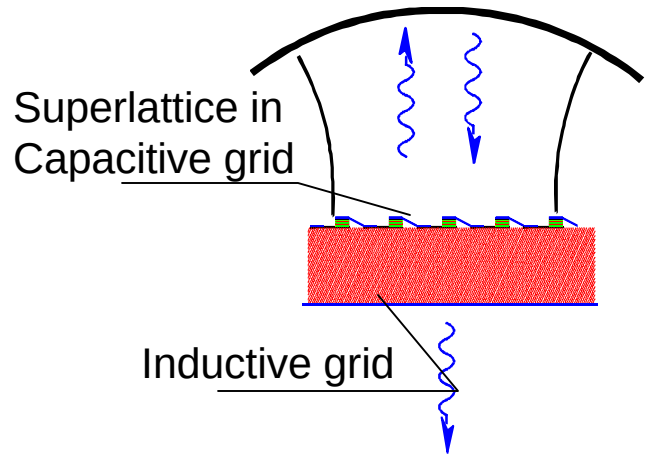
- **Band structure**
- **Contact resistance**

Concept

# Solid State Terahertz Source

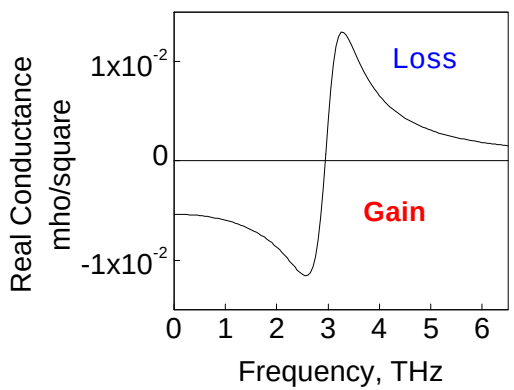



InAs/AlSb Superlattice in an electric field

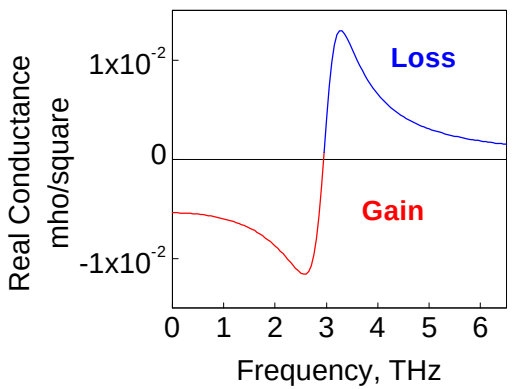


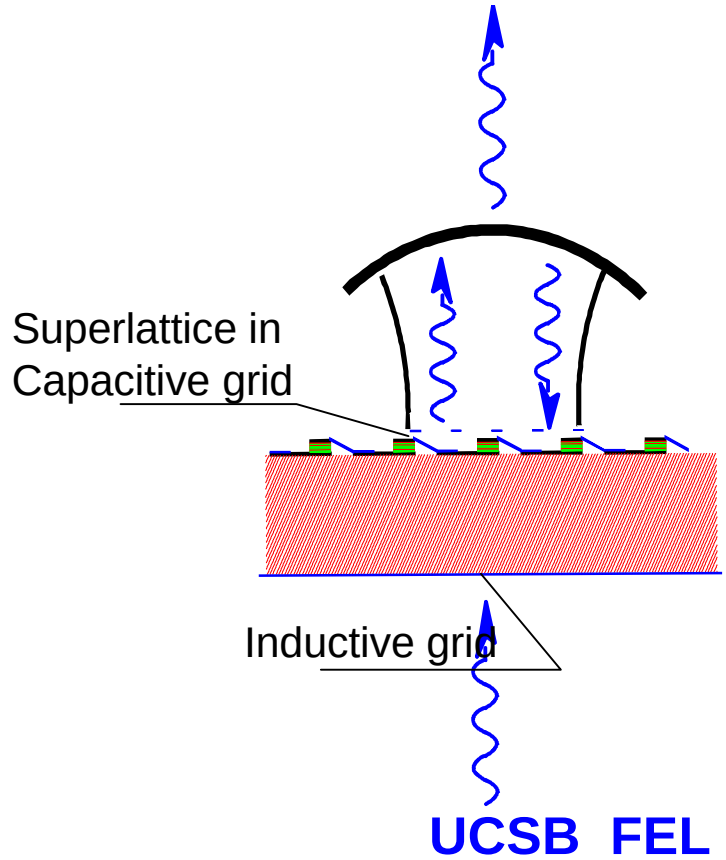

THz Cavity

Evolves⇒
< 600 GHz
Negative conductance
>600GHz
Quantum transition &
"Laser like" gain,



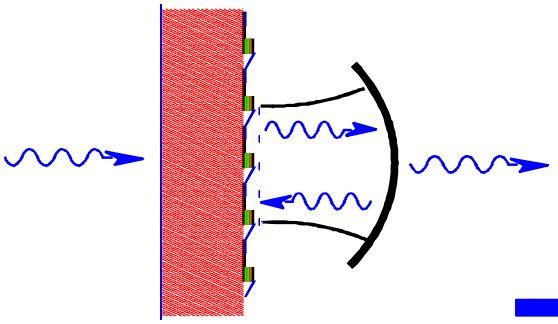

Superlattice in Capacitive grid



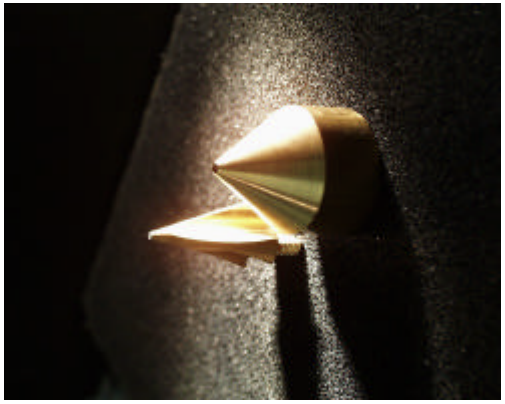




# THz Transmission cavity

# THz Transmission Cavity Spectrometer



**From FEL**

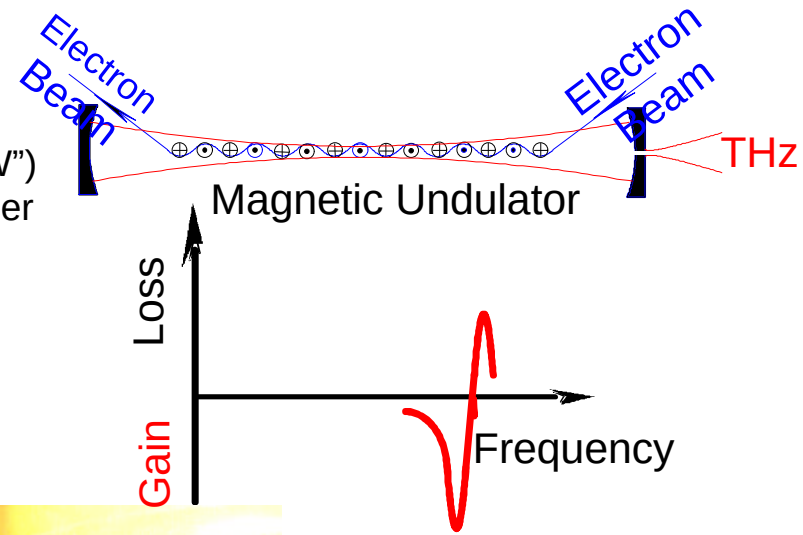


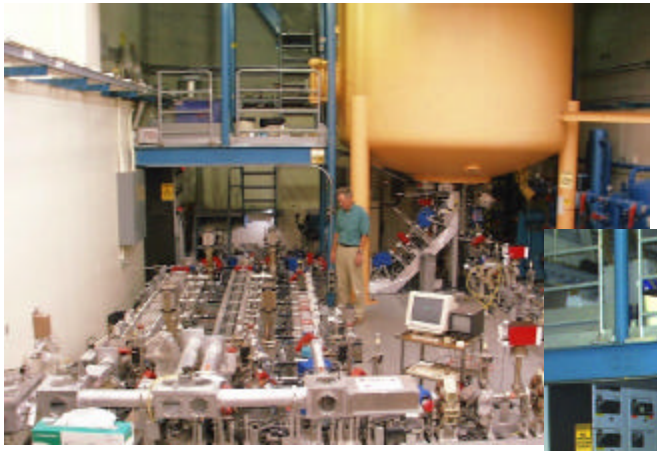
**To detector**

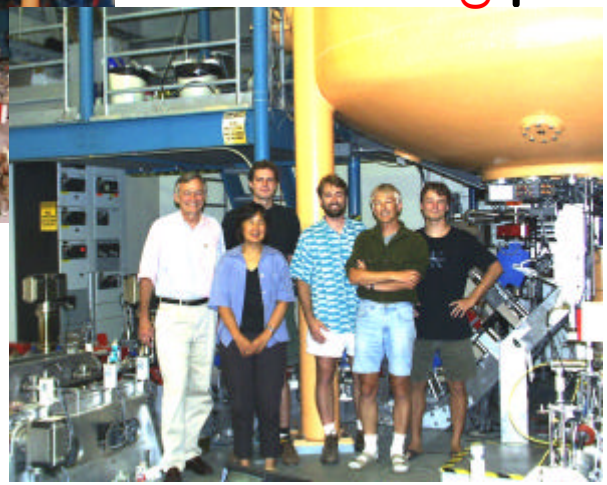
**Measure ΔT/T vs Bias Voltage vs THz Frequency**

# UCSB - Free-electron Lasers

- Kilowatts, 500 W - 5 kW
- Tunable terahertz radiation
  120 GHz to 4.8 THz ( ⇒ 10 THz )
  2.5 mm to 60 µm ( ⇒ 30 µm )
- 1- 20 µsecs, 1 Hz repetition rate ("Quasi - CW")
  ➡ 1 picosec to 4 nanosecond Pulse Slicer





**THz Oscillator Project**

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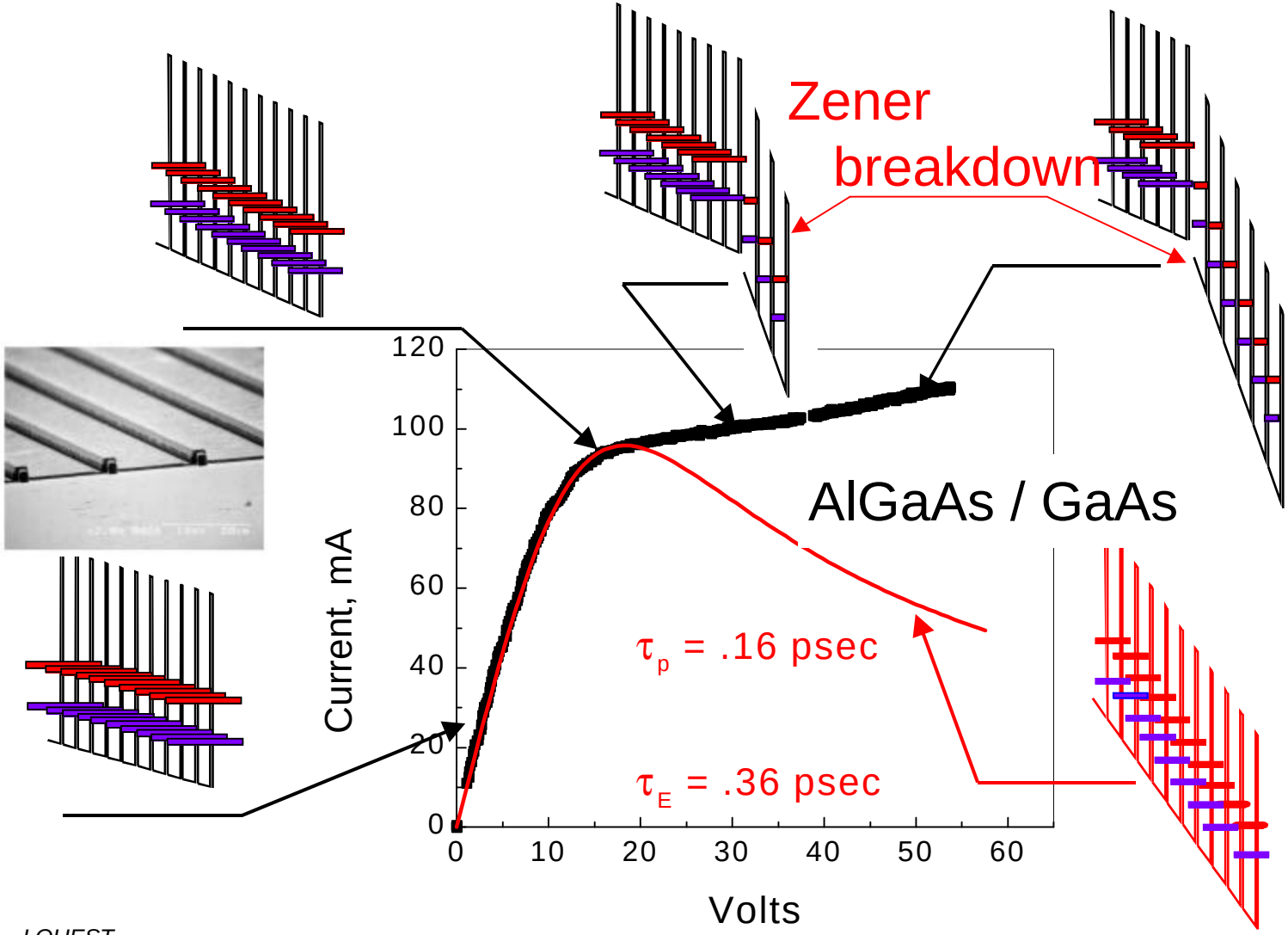
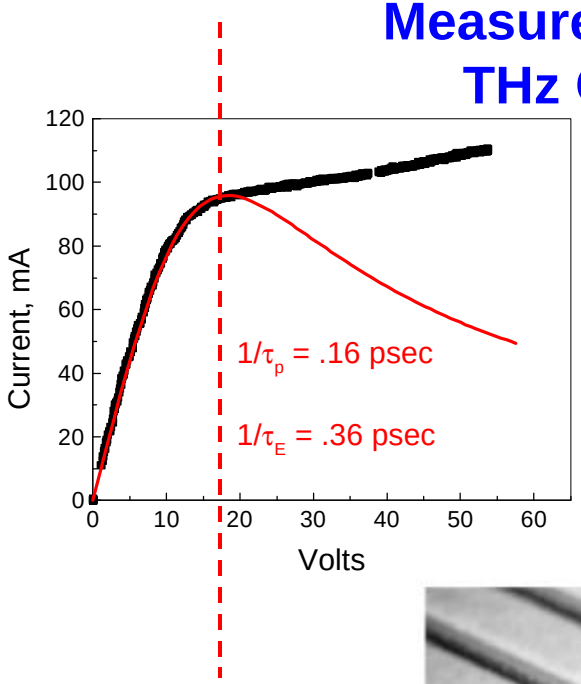
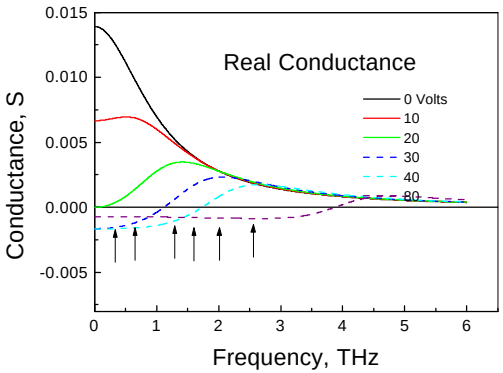
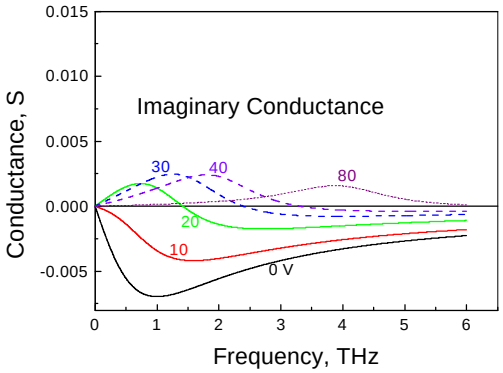
# Critical issue: **Electric Field Domains**



# Measure the Change in THz Conductance under Electrical Bias

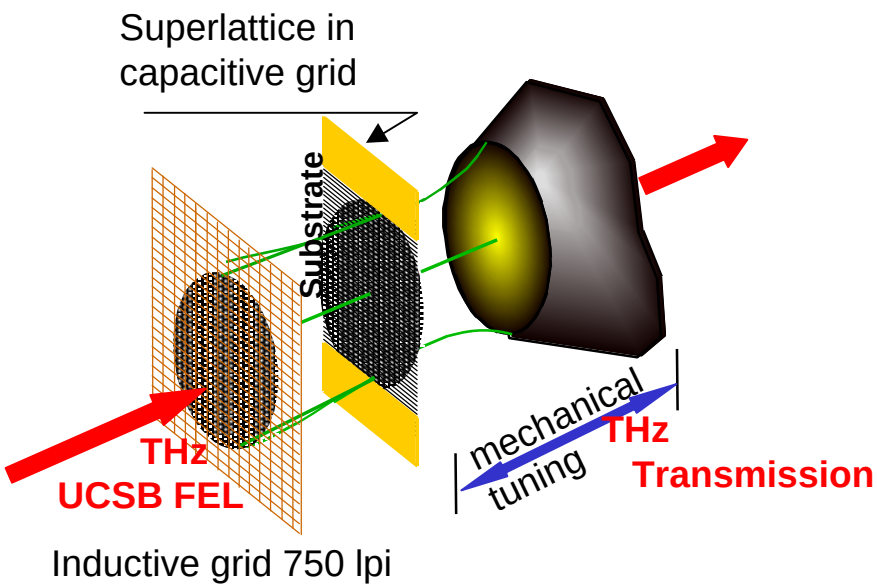


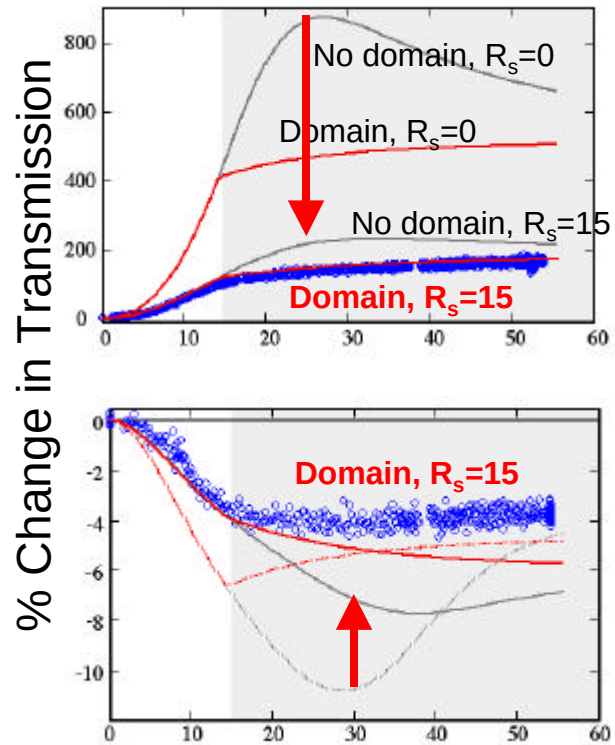


# Critical issue: Contact resistance

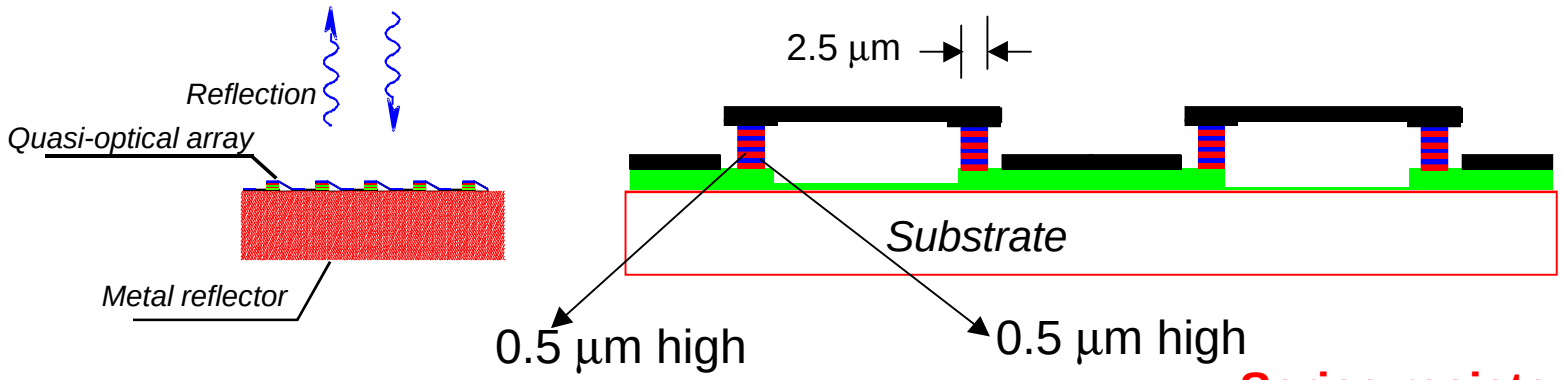
# Modeling:
# Domain formation and contact resistance



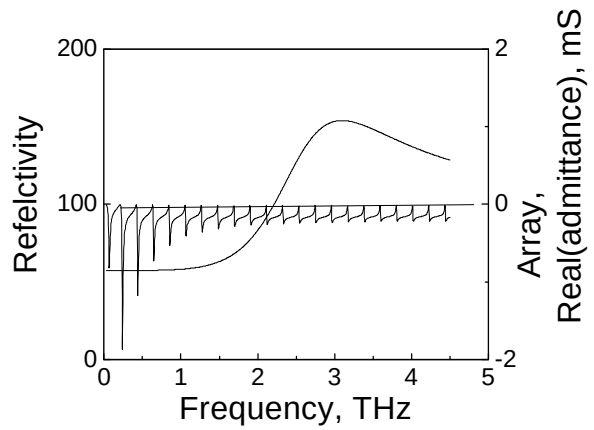



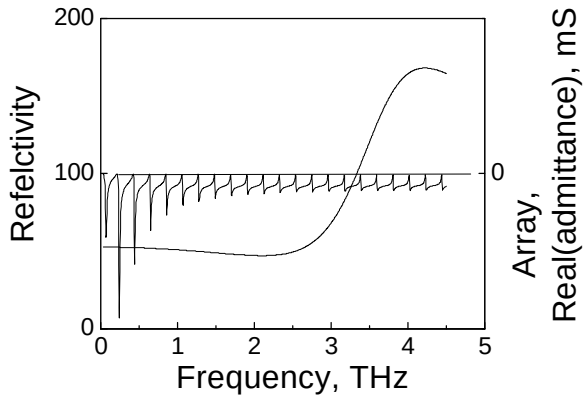

Effective contact resistance of ~6 x $10^{-6}$ $\Omega \cdot cm^2$

# Model: Refection Gain, GaAs/AlGaAs Superlattice Array



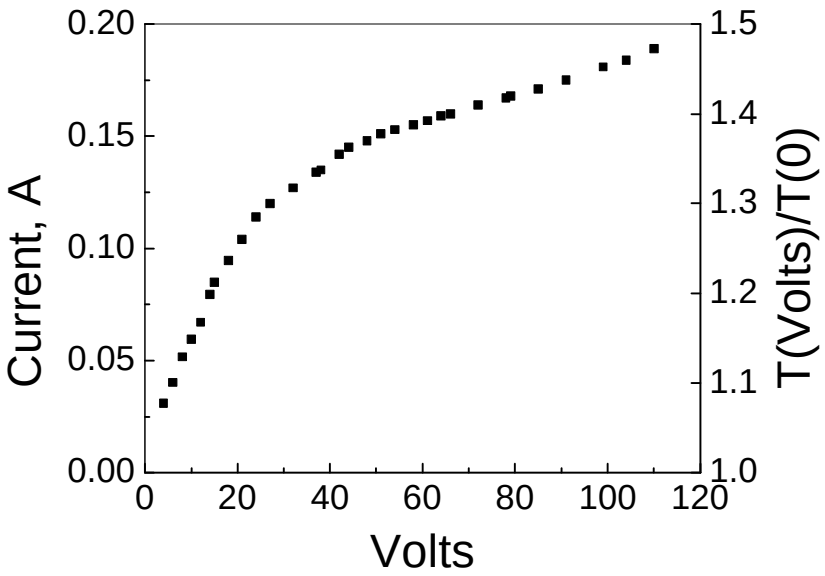

**Series resistance !!**

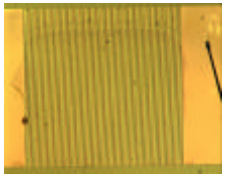


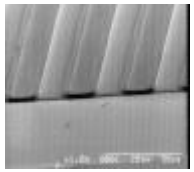



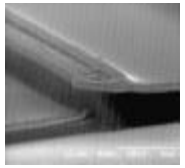
# InGaAs/AlAs:
# Domain suppression with THz fields

## I-V: InGaAs/AlAs



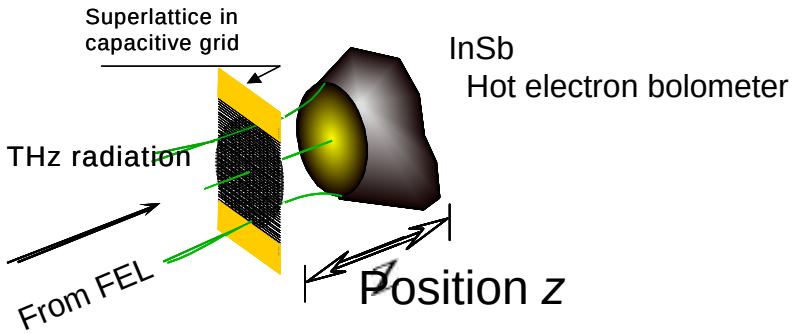




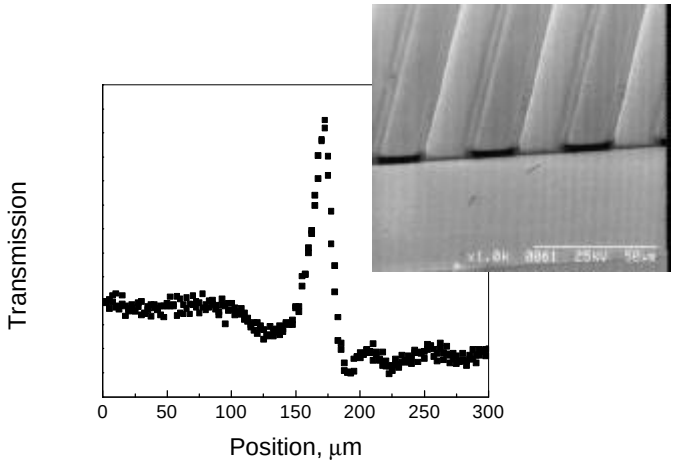
1mL AlAs/ 40 mL InGaAs
SB2891

InGaAs Superlattices in Quasi-Optical Arrays

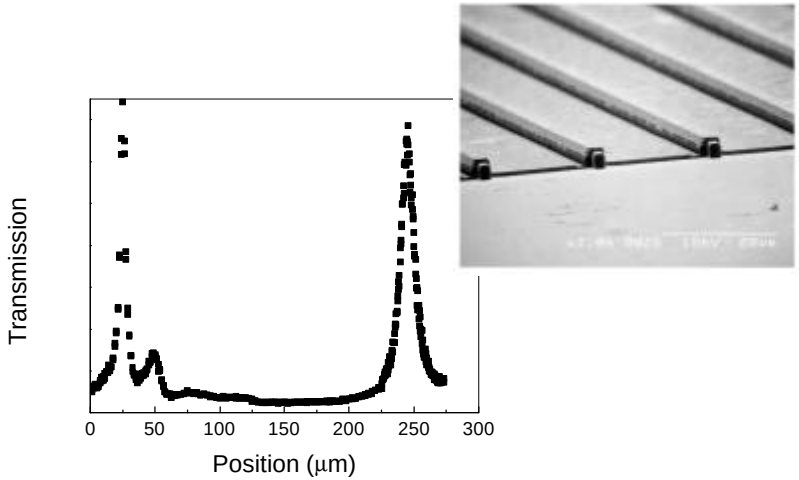
# Millimeter Scale Confocal Resonator




**510 GHz**




**InGaAs/AlAs**



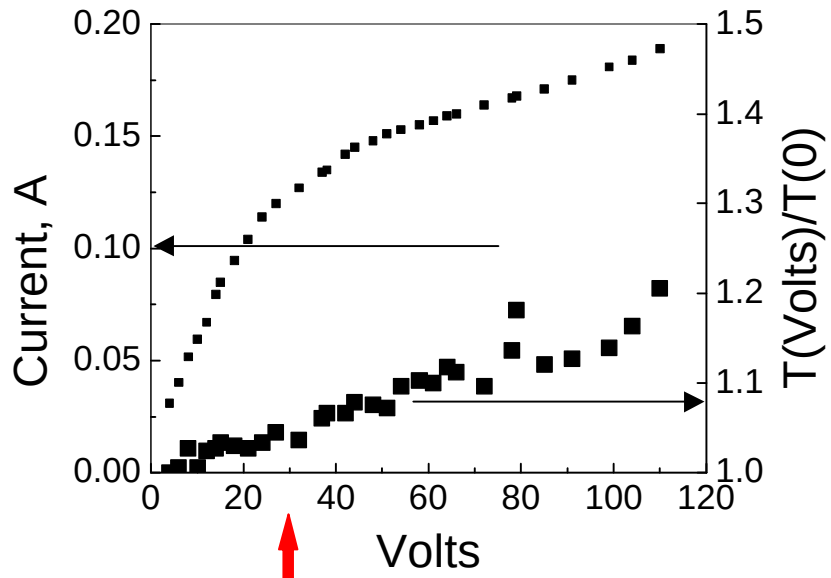

**GaAs/AlGaAs**

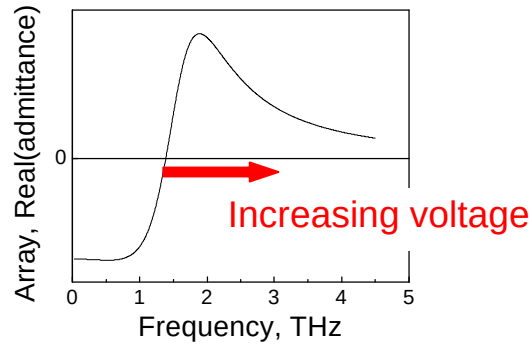
InGaAs/AlAs

# Voltage Modulated Transmission, 513 GHz

## (Terahertz Electric Field Dependence, InGaAs/AlAs)

See: H. Kroemer, “Large-amplitude oscillation dynamics and domain suppression in a superlattice Bloch oscillator”, cond-mat/0009311




$$n_B = 500\ GHz$$

InGaAs/AlAs

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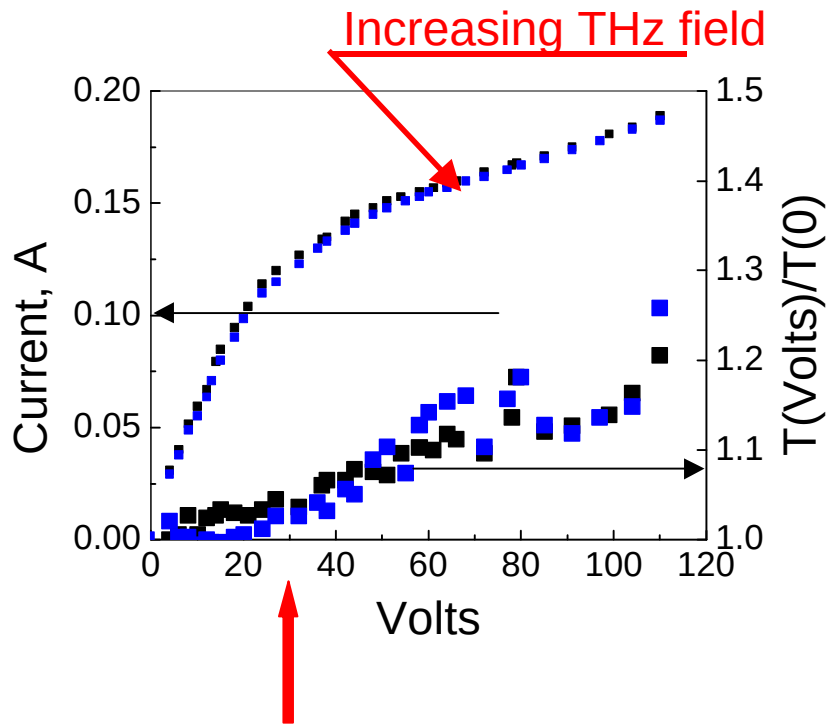


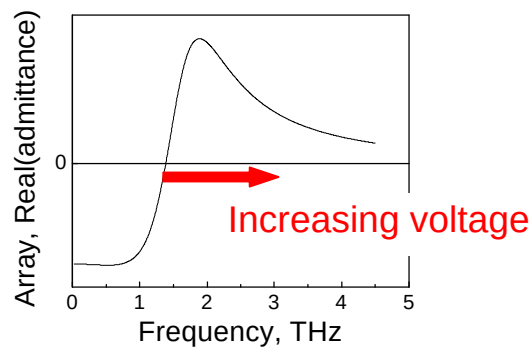


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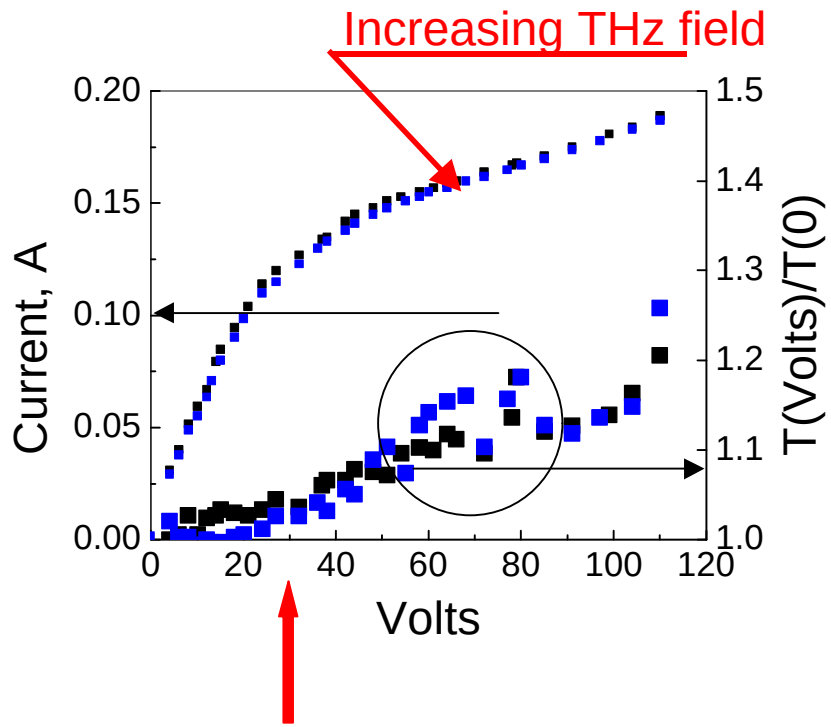


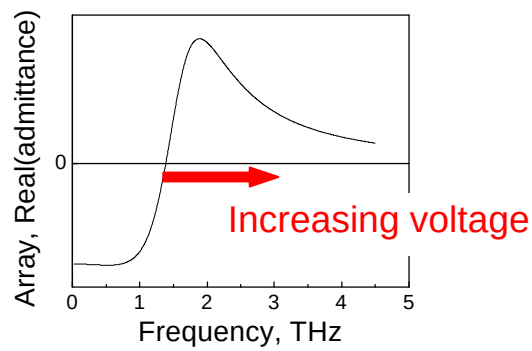


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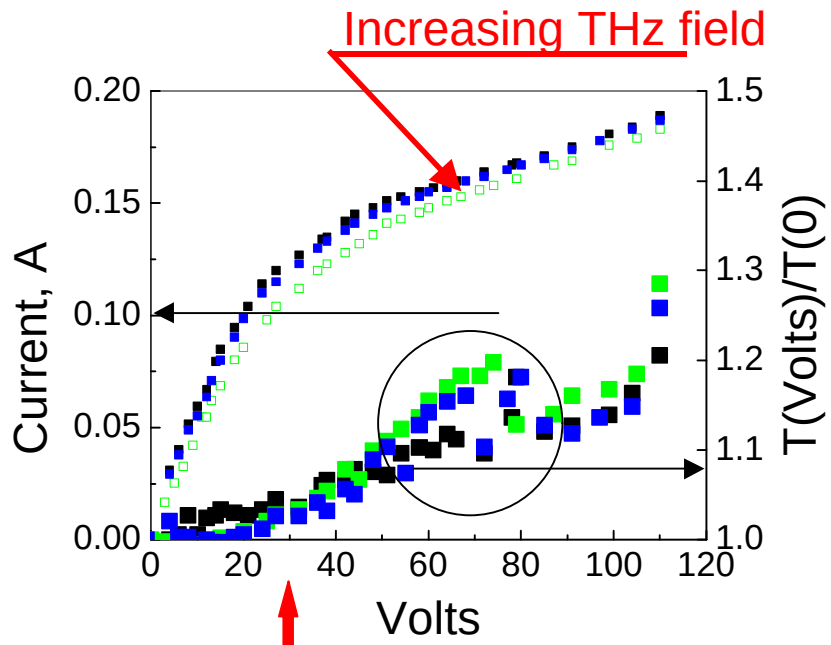


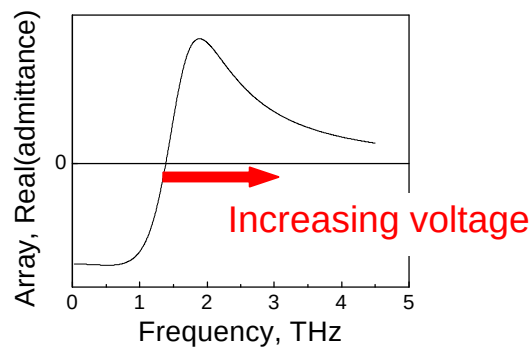


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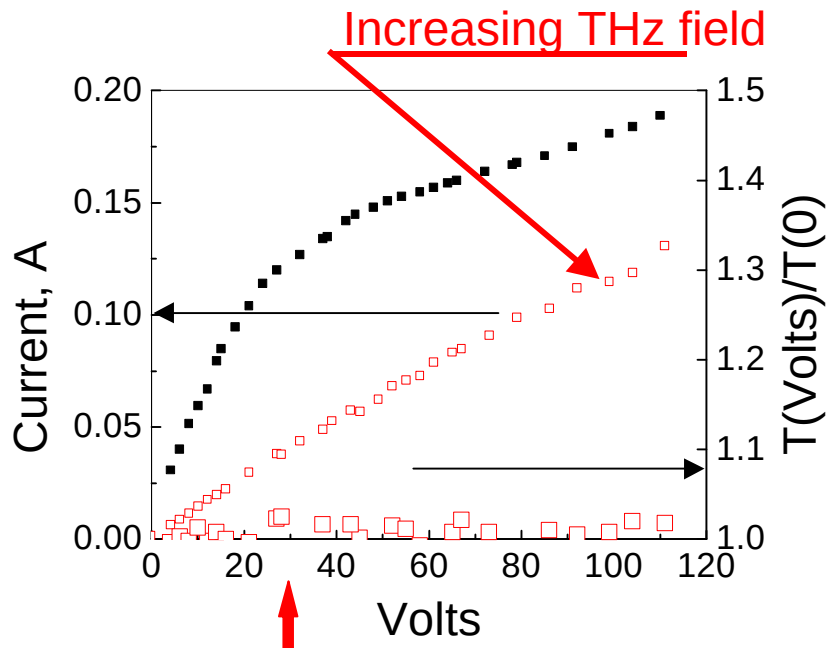
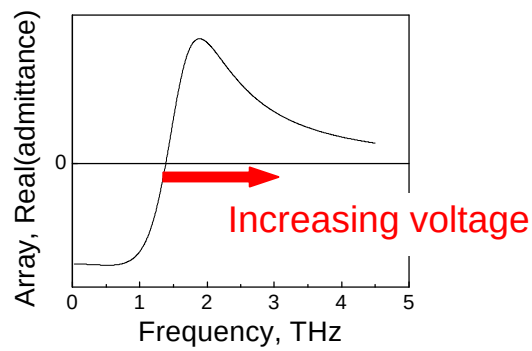
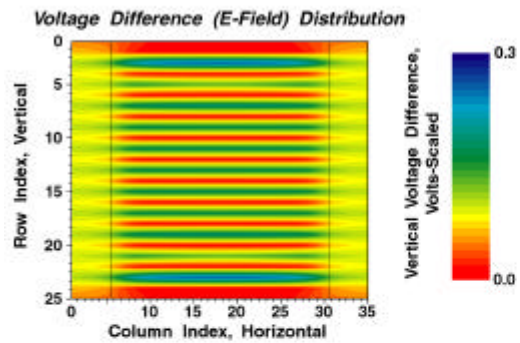


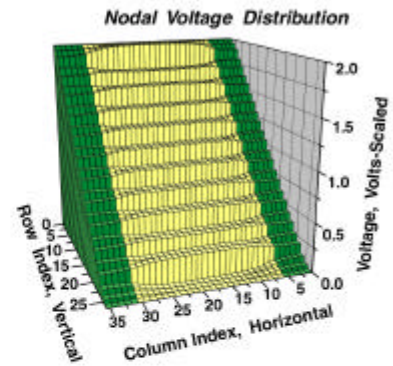



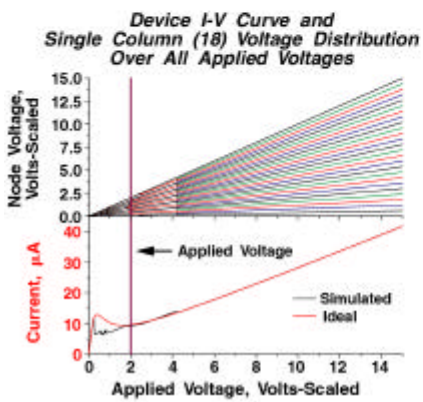

$$n_B = 500\ GHz$$

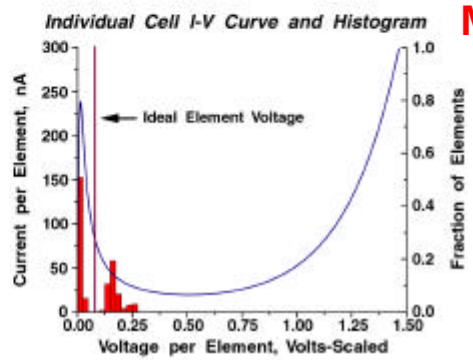
# Stabilization by Microshunt (Edge Regrowth)

**SIMULATED VOLTAGE DISTRIBUTION OF BLOCH OSCILLATOR DEVICE**
**( VIN = 2.0 Volts, Down Sweep; 2 x 5 micron Device, 80 nm Edge Resistor;**
**HSPICE Transient Simulations Performed by Mayo in Collaboration with**
**UCSB Under the DARPA Terahertz Technology Program )**




05 / 2000 / ESD / 16961

**See:**
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**Mayo Foundation**

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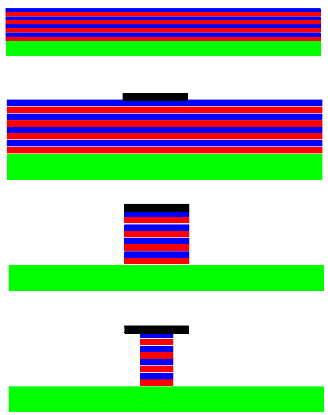
*Quantum Engineering, Science and Technology*

Center for Terahertz Science and Technology
UC Santa Barbara
http://www.qi.ucsb.edu/

# “Funky” Edge Regrowth: In-situ etching/regrowth



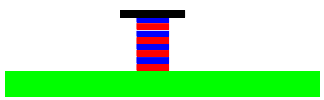
Superlattice wafer

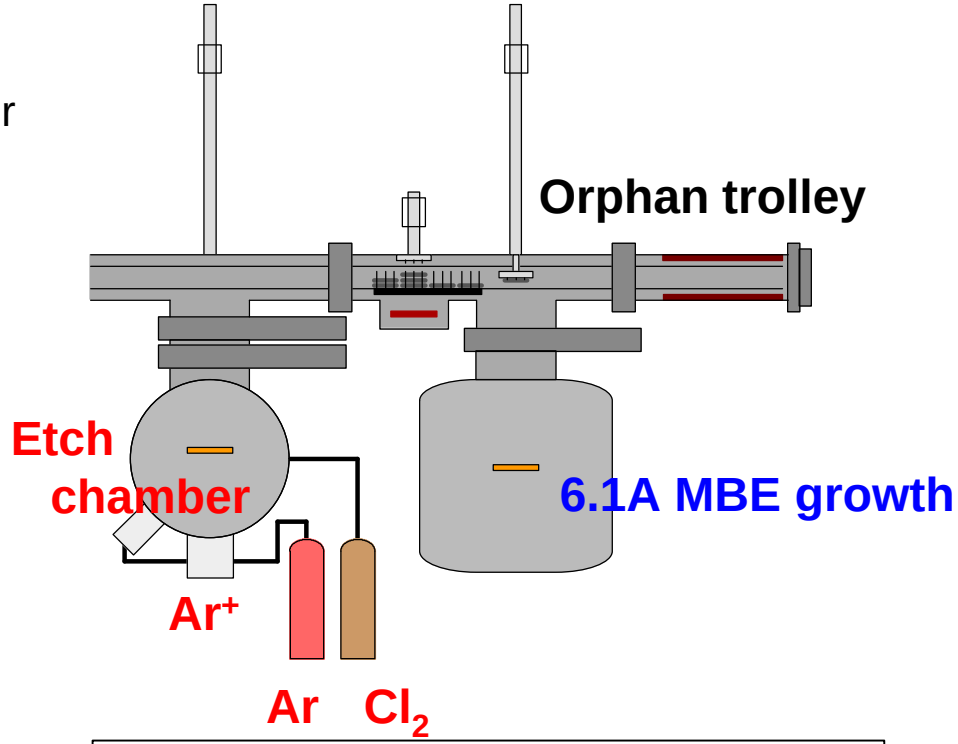
Ti mask

CAIBE, Ar, $Cl_2$

$Cl_2$, soak

MBE chamber:
Heat and
Reflow surface in As,Sb flux

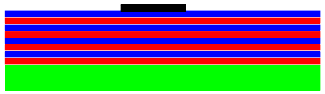




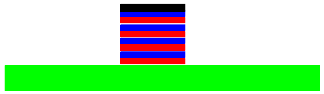

- **Heated substrate**
- **UHV**
- **No atmospheric intervention**

# “Funky” edge regrowth:  In progress

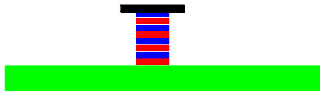
Superlattice wafer



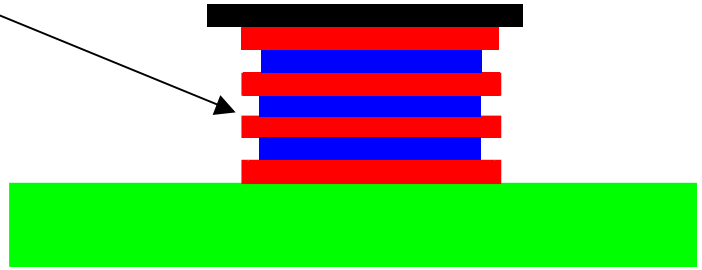
Ti mask



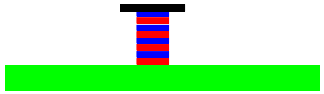
CAIBE, Ar, $Cl_2$



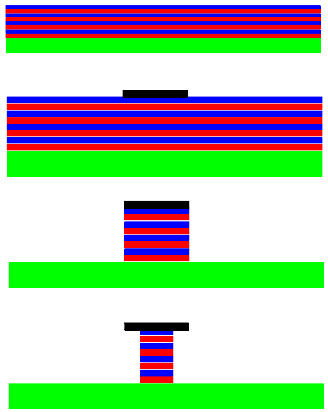
**$Cl_2$, soak**



MBE chamber:
Heat and
Reflow surface in As,Sb flux



# “Funky” edge regrowth:  In progress



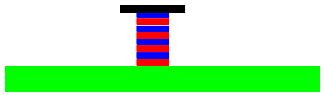
Superlattice wafer

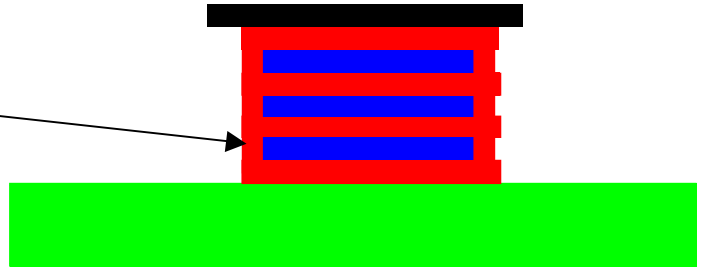
Ti mask

CAIBE, Ar, $Cl_2$

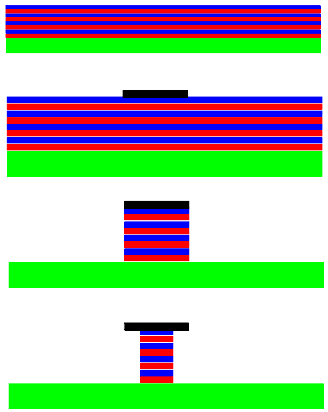
$Cl_2$, soak

**MBE chamber:**
**Heat and**
**Reflow surface in As,Sb flux**





# “Funky” edge regrowth:  In progress



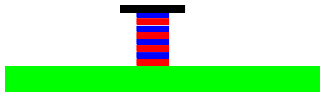
Superlattice wafer

Ti mask

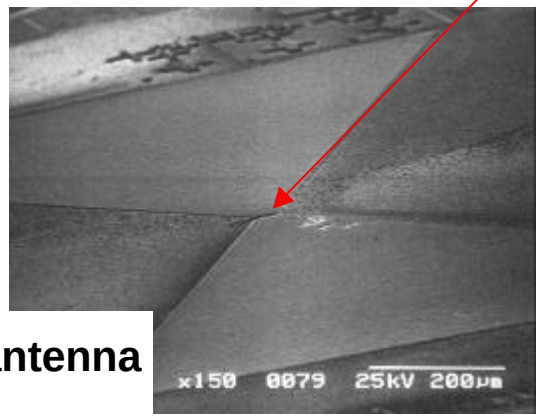
CAIBE, Ar, $Cl_2$

$Cl_2$, soak

MBE chamber:
Heat and
Reflow surface in As,Sb flux



Test element of the QOA



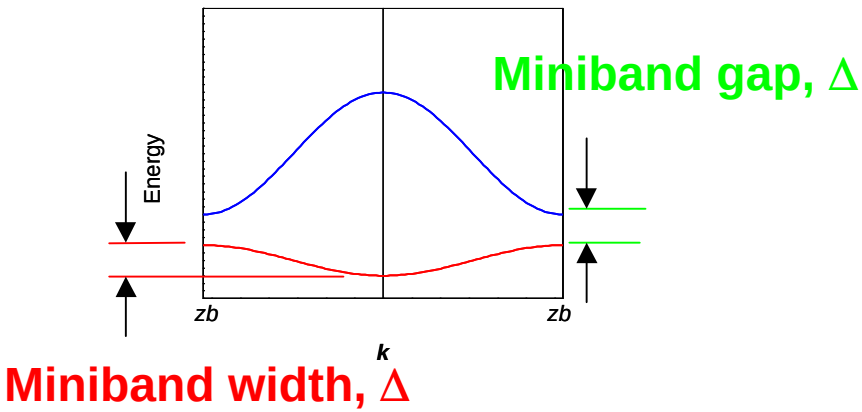

**Continue:**

**Integrate in antenna**

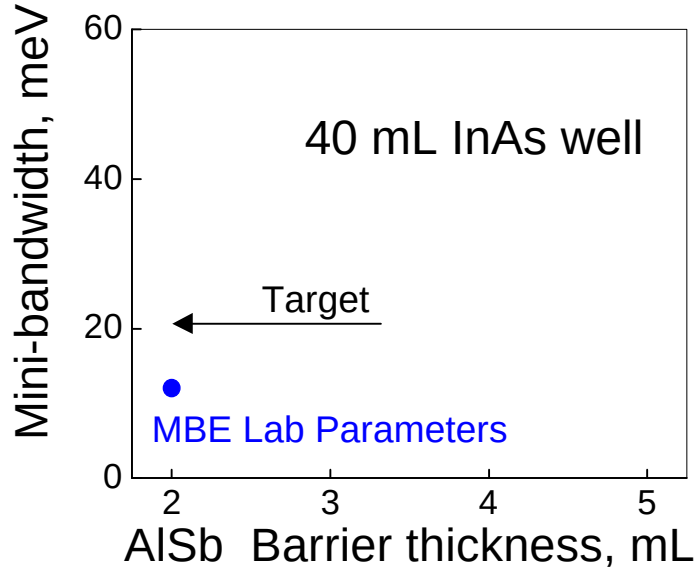
**I-V’s**

**THz photon assisted transport**

# InAs/AlSb Mini-bandstructure



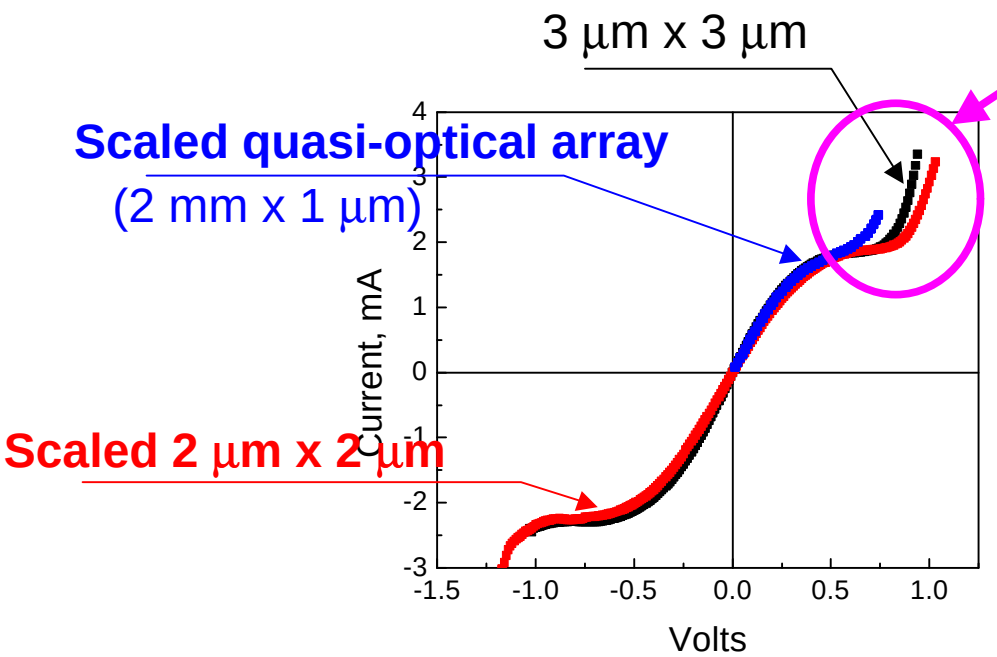

Target 20 meV




H. Kroemer et al., J. Vac. Sci. Technol., **B10**, 1769 (1992).

# InAs / AlSb superlattices

## Early Breakdown (Reversible)

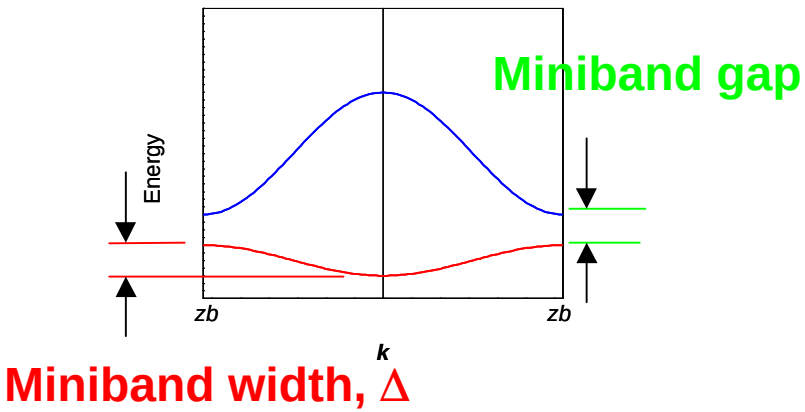



Zener breakdown?
Super lattice ⇒
Super-super lattice

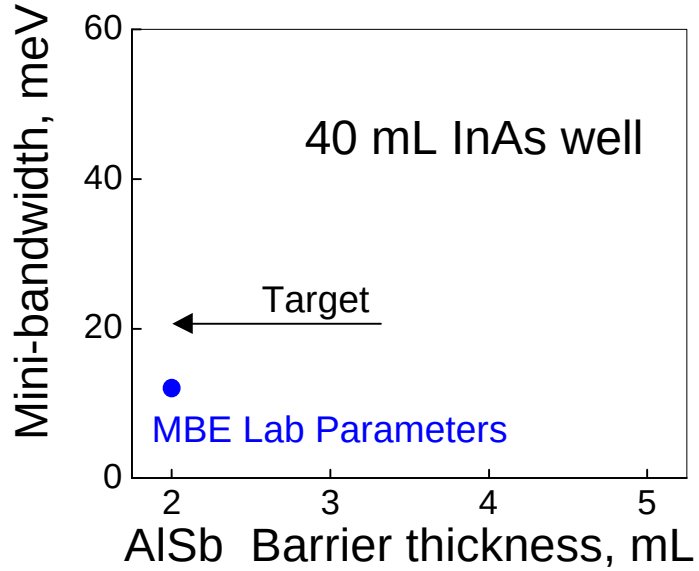
Hole impact ionization?
AlSb ⇒ AlAs

InAs/AlSb 2mL / 40 mL

# InAs/AlSb Mini-bandstructure

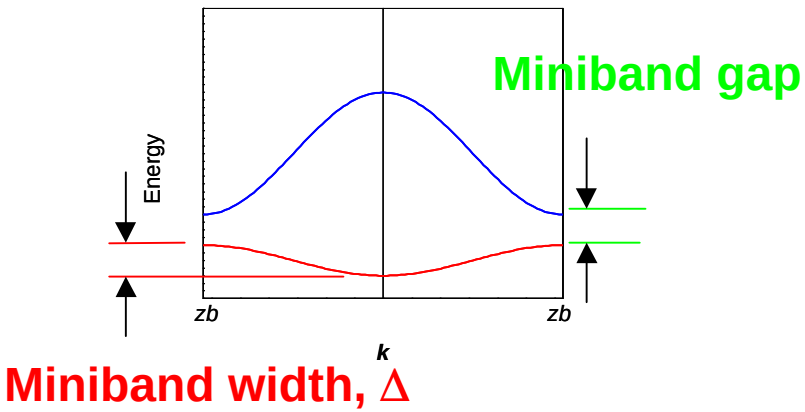



Target 20 meV

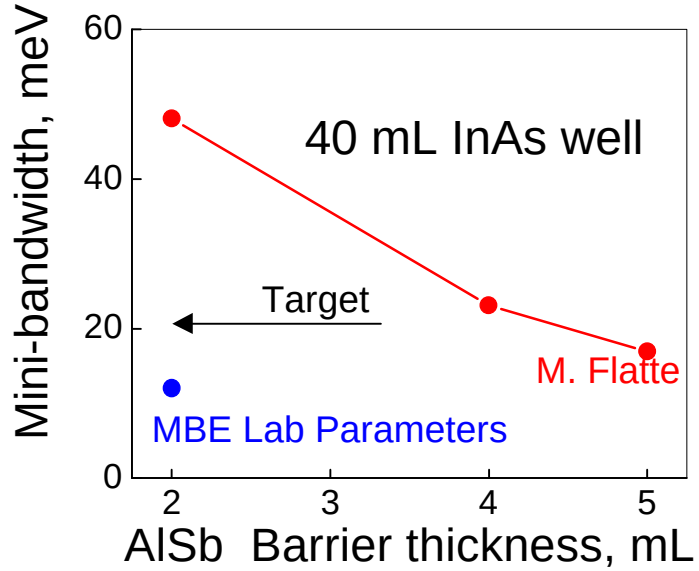



H. Kroemer et al., J. Vac. Sci. Technol., **B10**, 1769 (1992).

# InAs/AlSb Mini-bandstructure

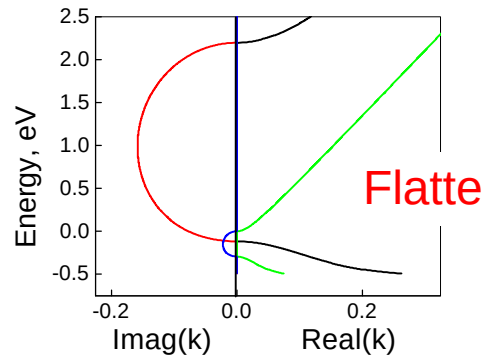


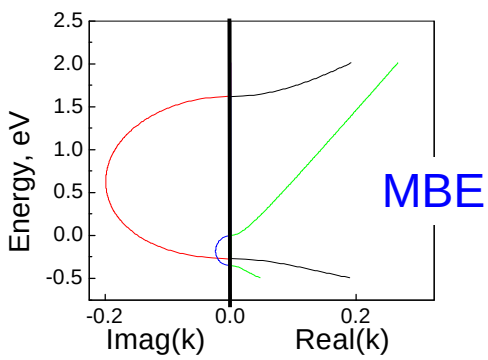

Target 20 meV

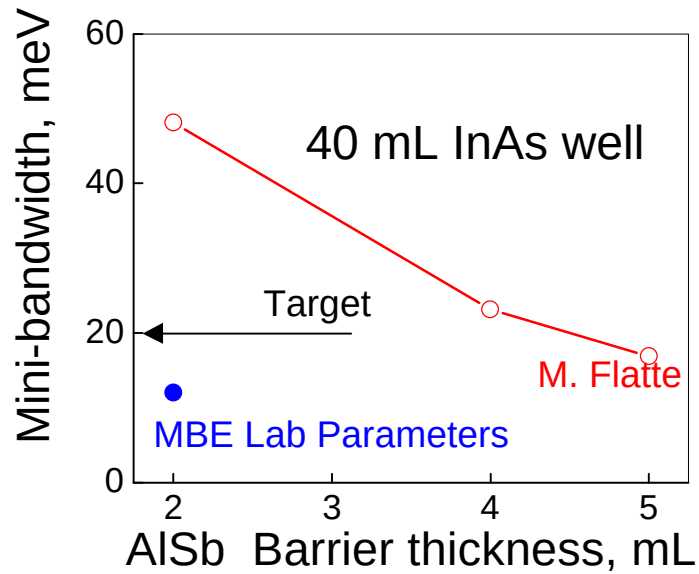



H. Kroemer et al., J. Vac. Sci. Technol., **B10**, 1769 (1992).

# InAs/AlSb Mini-bandstructure

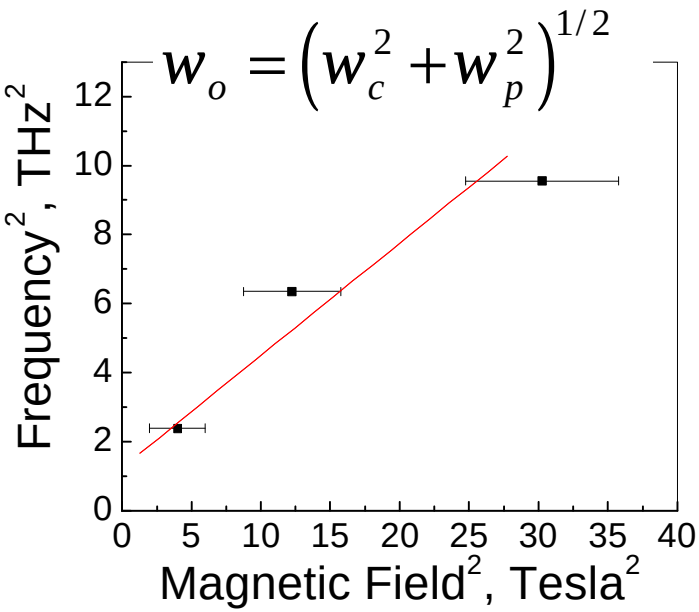


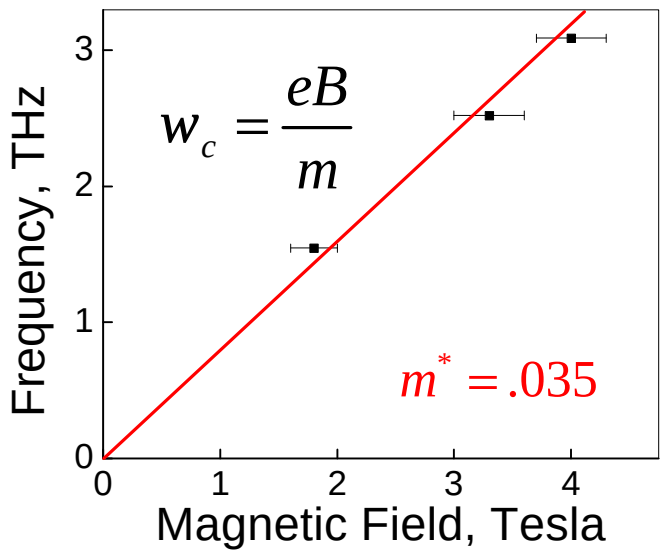



# Cyclotron Resonance in the Miniband

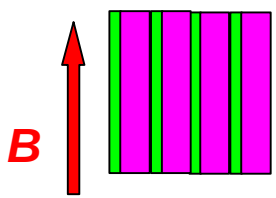
**T = 50 K**

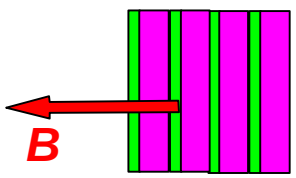



$m_s = .07$

$n = 1.4 \cdot 10^{16}\ cm^{-3}$

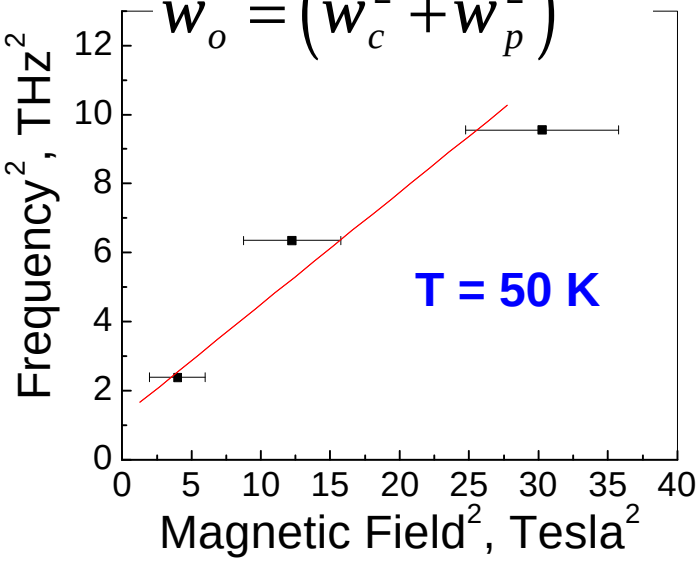


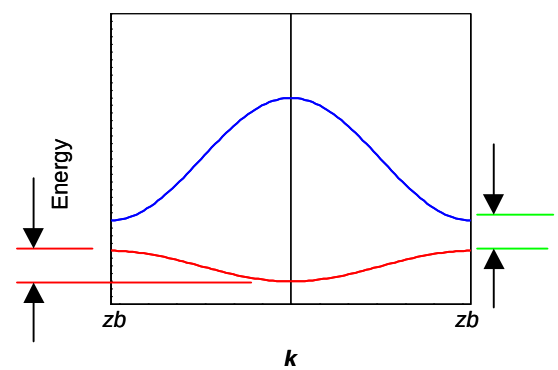




$n_{Hall} = 4 \cdot 10^{16}\ cm^{-3}$

# Cyclotron Resonance in the Miniband

$$w_o = \left(w_c^2 + w_p^2\right)^{1/2}$$

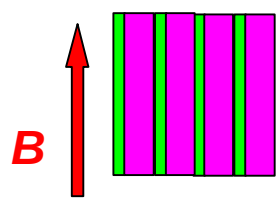



**Miniband width, $\Delta$**

$$m_s = .07$$

$$n = 1.4 \cdot 10^{16}\ cm^{-3}$$




$$n_{Hall} = 4 \cdot 10^{16}\ cm^{-3}$$

**4mL AlSb/ 40 mL InAs**

**$D$ ~ 18 meV**
**$m_s$ = .07**
**$t_p$ = .25 $10^{-12}$ secs**

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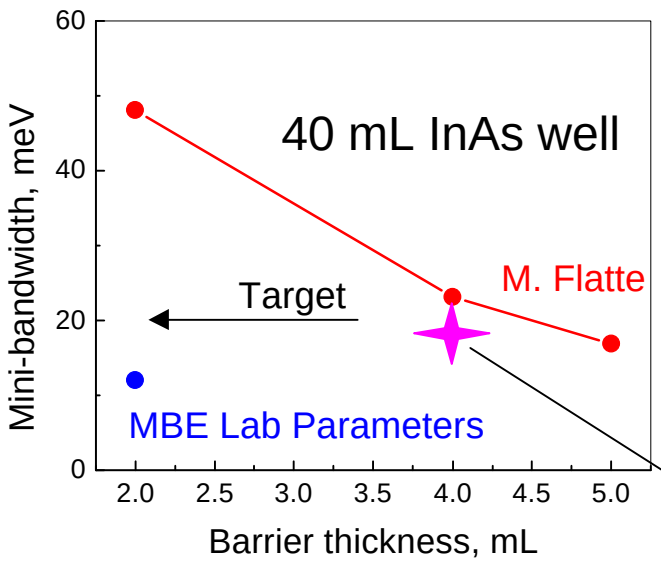
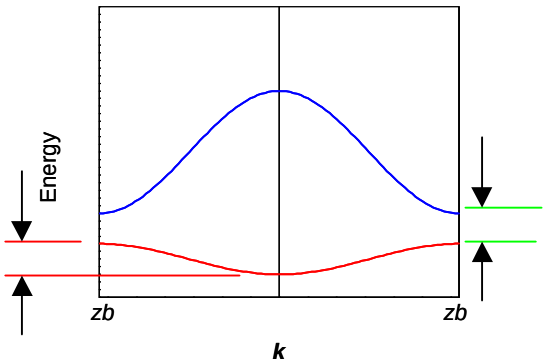
*Institute for*
*Quantum Engineering, Science and Technology*

Center for Terahertz Science and Technology
UC Santa Barbara
http://www.qi.ucsb.edu/

# InAs/AlSb Mini-bandstructure




**Miniband width, Δ**

Target 20 meV

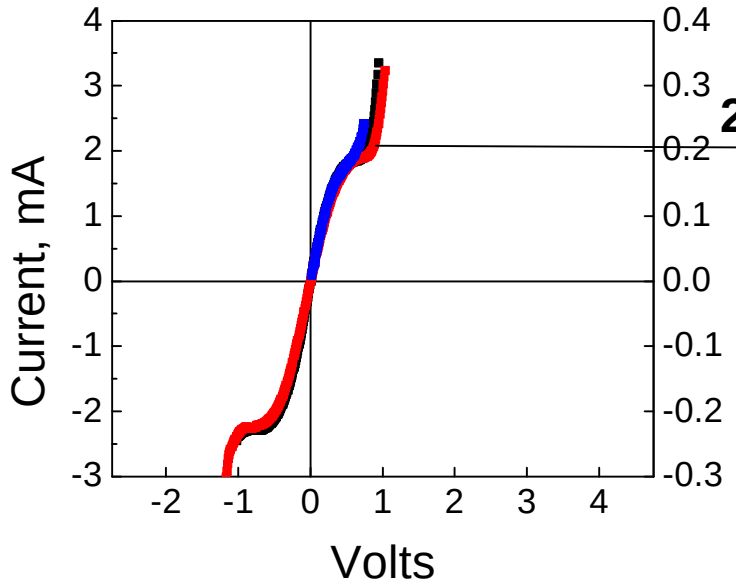
**4mL AlSb/ 40 mL InAs**

**$D$ ~ 18 meV**

**$m_s$ = .07**

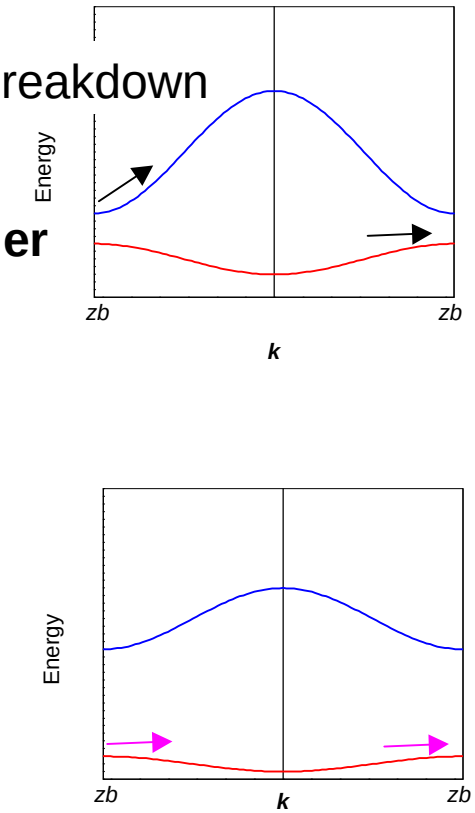
**$t_p$ = .25 $10^{-12}$ secs**

# Zener Breakdown

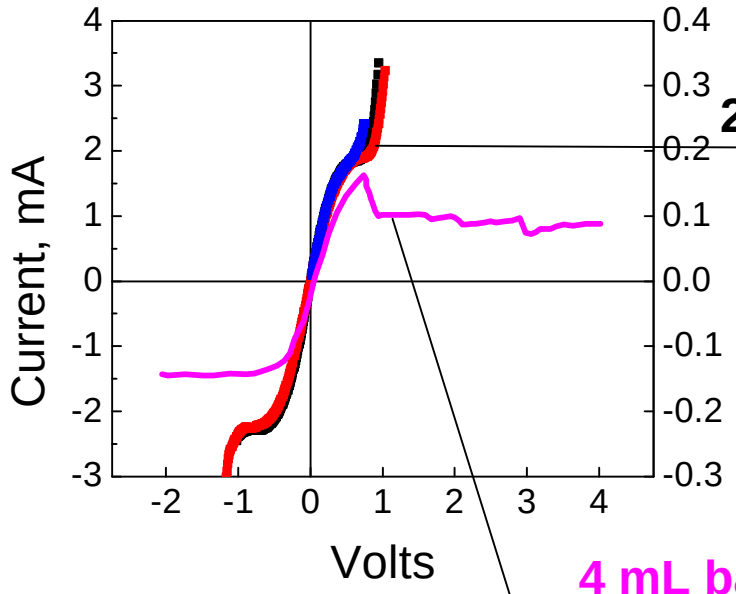



**2 mL barrier**

Zener breakdown



# Zener Breakdown

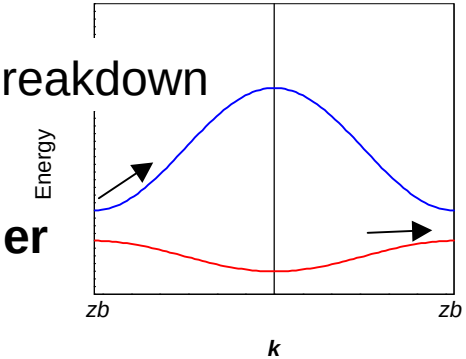


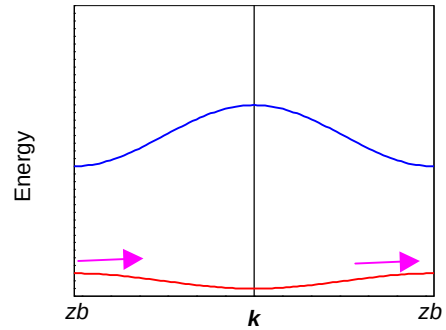

**2 mL barrier**

**4 mL barrier**

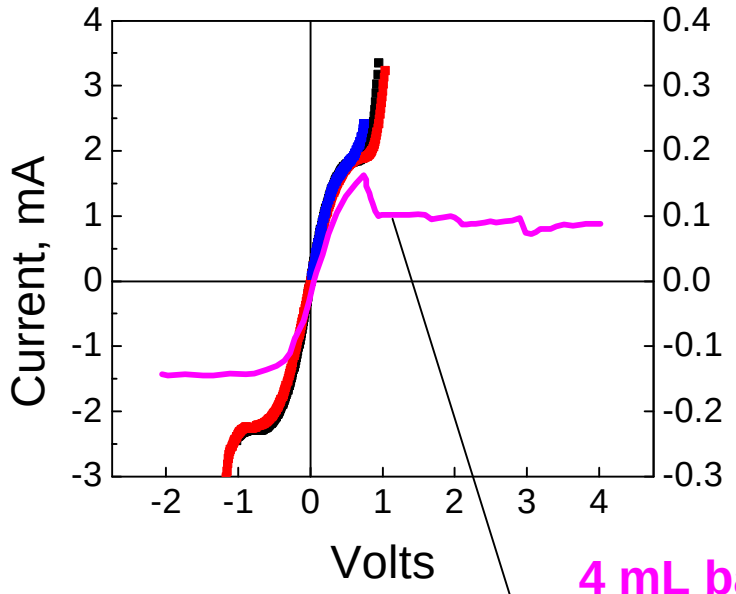
(SB2873)

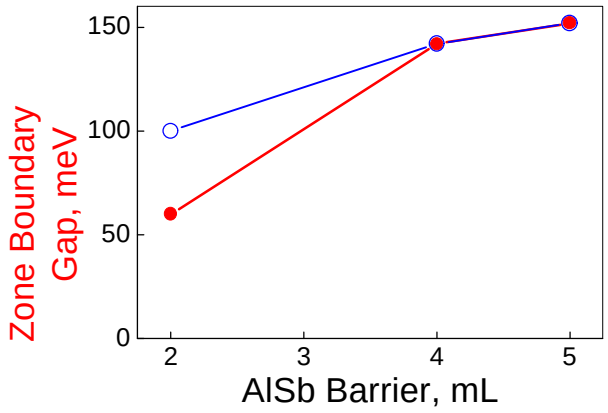
Zener breakdown



# Zener Breakdown ?

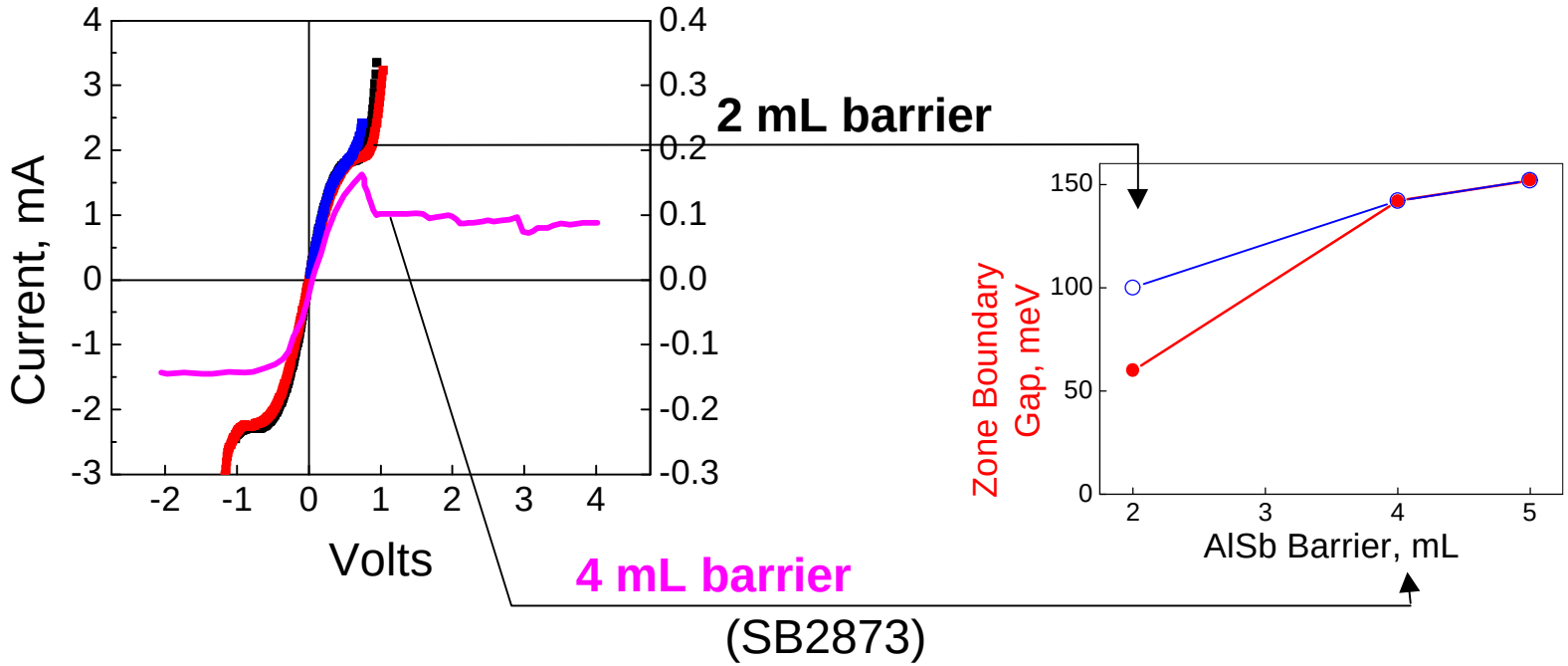



**4 mL barrier**

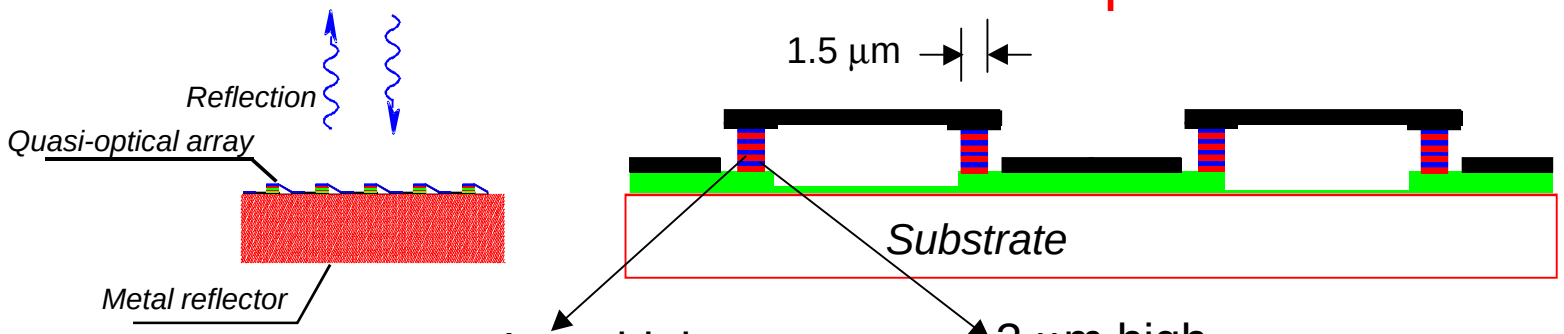
(SB2873)

# Zener Breakdown ?

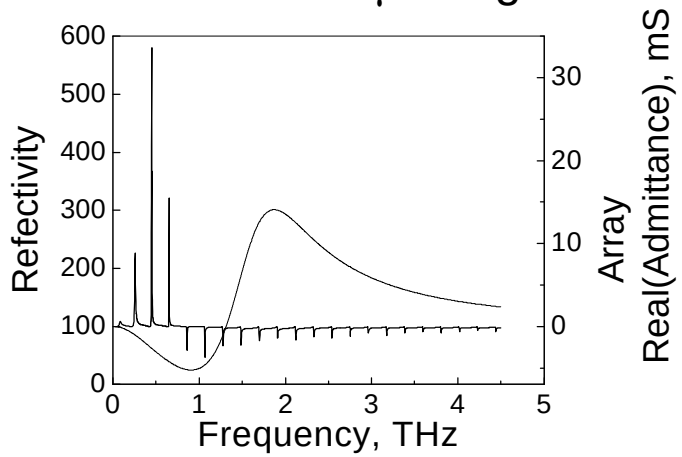


# Model Refection Gain, InAs/AlSb Superlattice Array

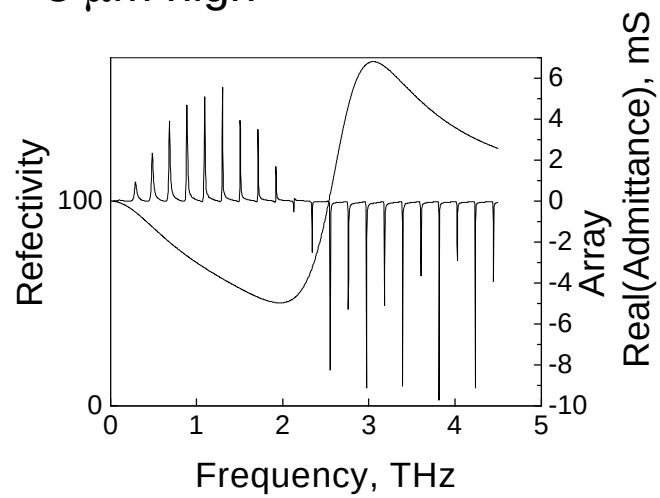
## - *With* measured miniband parameters -



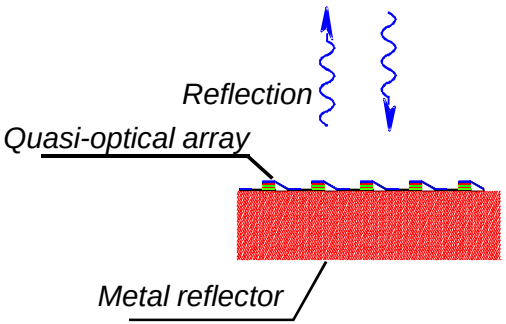

1 µm high

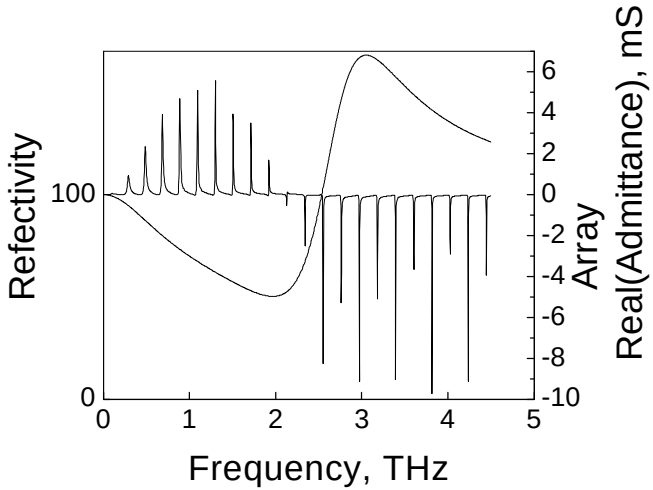



3 µm high

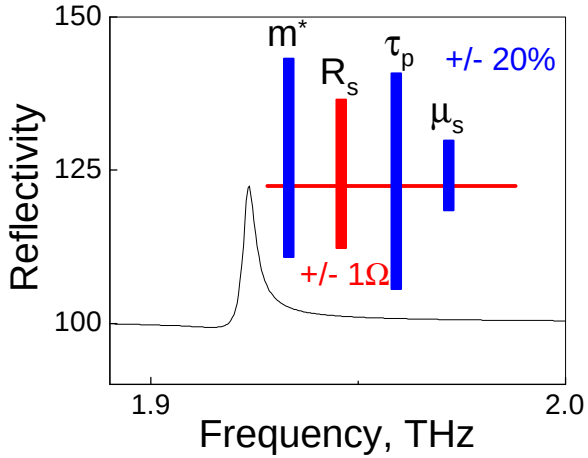


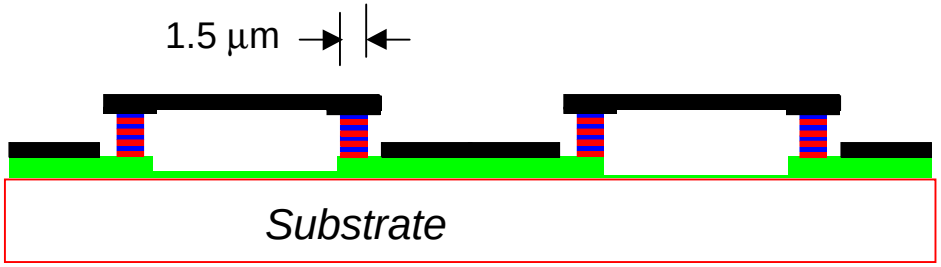
# Refection Gain, InAs/AlSb Superlattice Array




Sensitivity to material



# Where are we?

- GaAs / AlGaAs
  - Dynamical response of biased superlattices 300 GHz – 2.5 THz
  - Quantitative model
    - R's and C's
    - Domain formation / Zener breakdown
- InGaAs/AlAs
  - Modulated transmission thru quasi-optical arrays
  - Domain suppression by strong THz fields
- InAs/AlSb superlattices
  - Miniband structure – measured
  - Oscillator projected
  - Microshunts "working on it"

# Plans

InAs / AlSb

Continue new process for sidewall shunt.

Path

Process

χ I-V's

χ Terahertz photon assisted transport

χ Response of quasi-optical arrays

Continue measurements of terahertz loss and gain

Large signal response

χ Domain suppression

InGaAs / AlAs χ InAs / AlSb superlattices.

χ *Oscillator*