Photo-Semiconductors: Evolution from IR Detectors to THz Sources

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29 November 2021

A recent Book Chapter:

"Photoconductive THz Sources Driven at 1550 nm," E.R. Brown, B. Globisch, G. Carpintero del Barrio, A. Rivera, D. Segovia-Vargas, and A. Steiger, in *Fundamentals of Terahertz Devices and Applications*, ed. by D. Pavlidis (John Wiley and Sons, Inc., W. Sussex, UK, 2021).

Short Bio

29 November 2021

Elliott Brown, Professor of Physics and Electrical Engineering at Wright State University

Dr. Brown received his PhD degree in Applied Physics from the California Institute of Technology in 1985; PostDoc appointment at MIT Lincoln Laboratory

His research interest is in quantum-effect devices and sensors; mm-wave-to-THz technology of all sorts; resonant tunneling light emitters; and biomedical sensing and imaging.

220 peer-reviewed Journal articles and Book Chapters; 170 archival conference proceedings; 19 U.S. Patents

IEEE, APS, and OSA Fellowships; multiple Awards including one for Outstanding Achievement from the Office of the Secretary of Defense*

*for service at the Defense Advanced Research Projects Agency (DARPA) 1995-1998

Review of Photoelectric Effect

- If light is not being absorbed or emitted by matter, it tends to behave just like RF radiation, meaning that it can be modeled as a wave phenomenon, displaying the usual effects of reflection, refraction and scattering

- But if light is absorbed or emitted, it tends to behave in a corpuscular fashion (i.e., like a "particle")

- So light is a great example of the so-called "wave-particle duality": one of the most important concepts in quantum physics

- This particle is called a "photon" : a massless and chargless particle, but with energy and momentum

- This was first explained by Einstein (and was the subject of his Nobel prize on the photoelectric effect in 1921)

- The energy of the photon as a particle is $E = h\nu$, where h is Planck's constant $h = 6.626 \times 10^{-34}$ J-s , and ν is the frequency, $\nu = c/\lambda$ where c is the speed of light in vacuum, and λ is the wavelength

- As an example, consider the red light of a HeNe laser, for which λ = 632.8 nm, $\nu = 4.74 \times 10^{14}$ Hz, $h\nu = 3.14 \times 10^{-19}$ J, and $h\nu/e$ = 1.96 electron-volt [eV] (recall that the product of charge and voltage is energy)

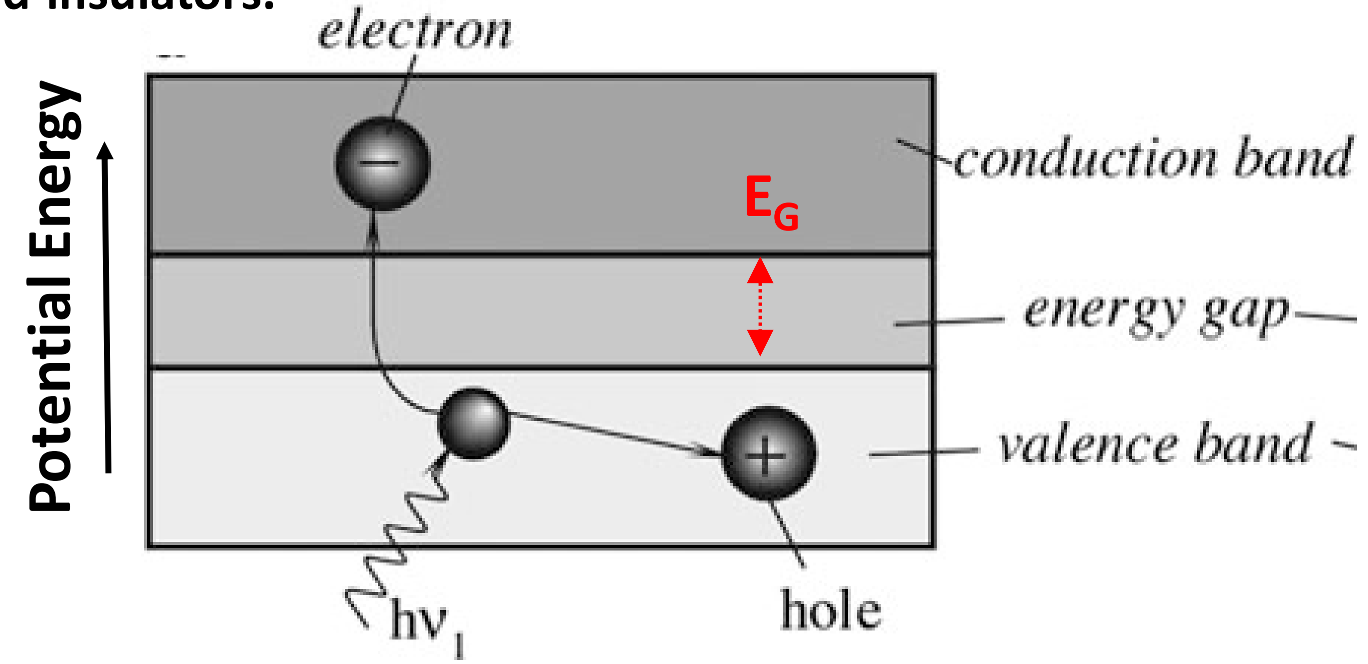
Internal Photoelectric Effect

- Similar conceptually to the original photoelectric effect describing photo-emission from a solid-state "cathode" emitting into vacuum toward an "anode".

- However, the "barrier" is not in real space, but rather in energy space. It is just the "band-gap" that occurs naturally in normal semiconductors and insulators.

- If $h\nu \geq E_G$, then a single photon can excite a bound electron in the valence band to free electron in the conduction band.

- And as a bonus, a free "hole" will be created in the valence band, that can also provide photocurrent (although usually with mobility less than the electron)



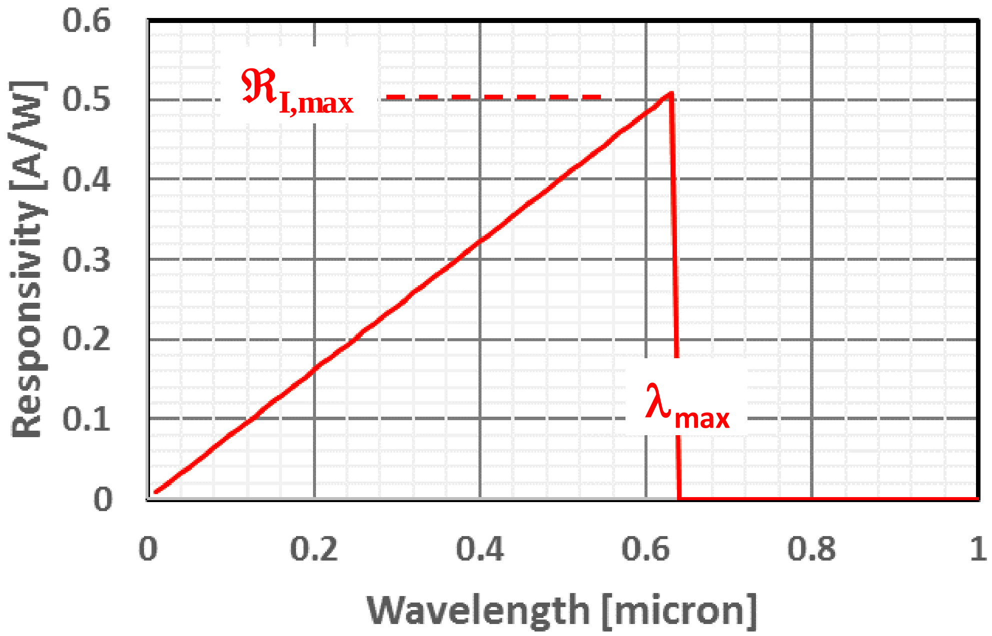
- The photocarrier generation rate is proportional to the average *absorbed* optical power, P_0

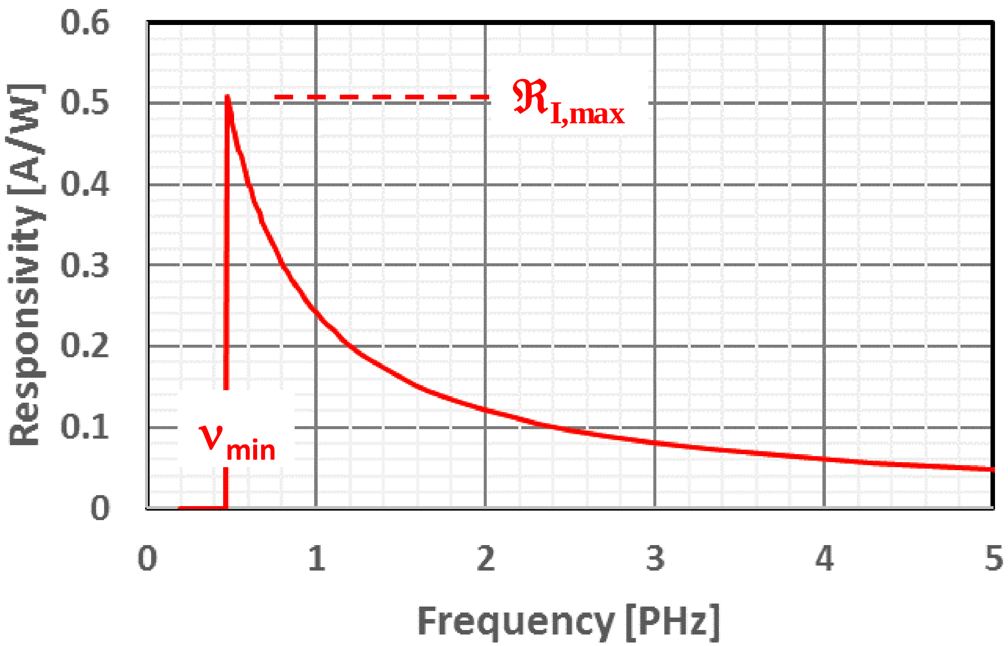
Light Sensors (cont)

- It is traditional to examine the photoresponse as a photocurrent with a current responsivity, $\Re_I \equiv I_p/P_O$, so that
  $\Re_I(\nu) = [\eta \cdot e/(h\nu)]\,\Theta(\nu - \nu_{min})$, and $\Re_I(\lambda) = [\eta \cdot e\cdot \lambda/(hc)]\,\Theta(\lambda_{max} - \lambda)$

- The plots of these two responsivities are shown below for E_G = 1.95 eV, corresponding to ν_{min} = 0.47×10^{15} Hz*, and λ_{max} = 0.64 um (in the "visible" red-light region); coupling factor Φ = 1.0 (ideal case)

- They both display the same maximum of $\Re_{I,max} = [\Phi\cdot e\cdot \lambda_{max}/(hc)] = [\Phi\cdot e/(h\nu_{min})] \approx 0.51$ A/W for Φ = 1.0





* 10^{15} is written as "peta", so 10^{15} Hz = 1 petahertz [PHz]

Light Sensors (cont)

- Important point: for the ideal photon detector, the maximum of $\Re_{I,max}$ = $[\Phi \cdot e\, \lambda_{max} /(hc)]$ increases with λ_{max}. Why is that ?

- Ans: because the photon rate $r_p = P_O/h\nu = \lambda\, P_O/hc$ increases with wavelength; i.e., the longer the λ, the *more photons per watt* of optical power.

- This leads to more fundamental metric for photon detectors which is the external quantum efficiency η_{ext} defined by

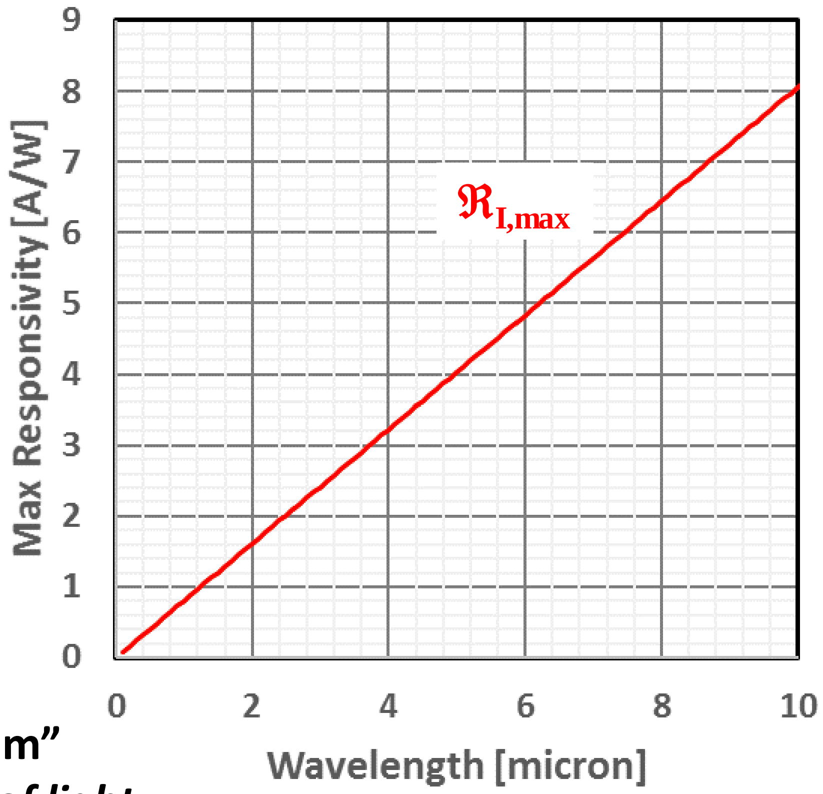
  η_{ext} ≡ electron rate in external circuit/incident photon rate

- But the electron rate is just $r_e = \Phi\, eP_O/(eh\nu) = I_p/e$, and the photon rate is $r_p = P_O/(h\nu)$

- Hence, $\eta_{ext} = \Phi$, the fraction of photons usefully absorbed. It is called a "quantum" efficiency since an electron is a *quantum of charge*, and a photon is a *quantum of light*

- η_{ext} = 1.0 defines the best possible performance of a photon detector at any λ

- *Key point: in all cases the photocurrent $I_P = A \cdot P_0 = B \cdot (E_0)^2$ where A and B are constants, and E_0 is the optical electric field*

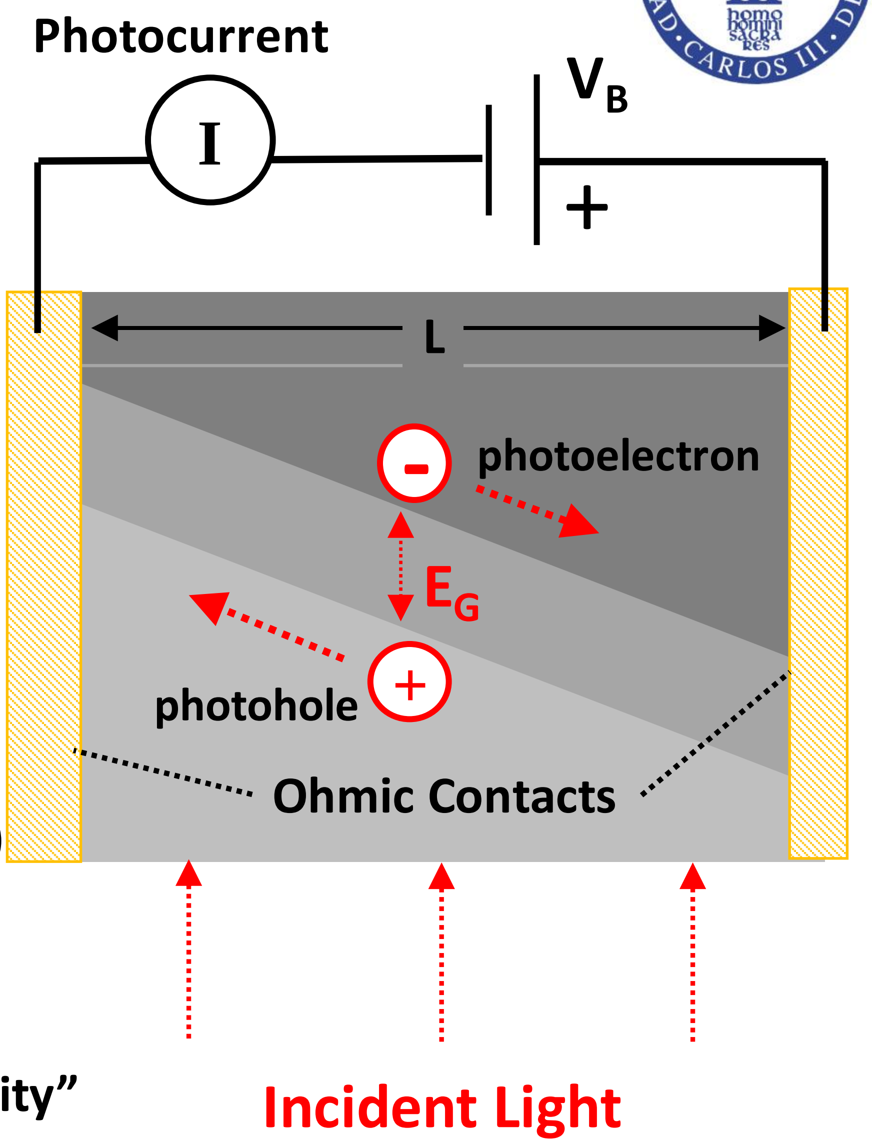


Semiconducting Light Detectors

- Now suppose we put "ohmic" contacts on opposite ends of the semiconductor and connect it to an external circuit with bias V.
- An absorbed photon ($h\nu \geq E_G$) will create a free electron and a free hole, which will then drift in opposite directions.
- As they "drift" toward their respective contacts, a photocurrent I_p will flow in the external circuit, immediately after excitation
- But they will only continue drifting for a time τ, which is the "lifetime" of the free electron (and hole).

(photoexcitation is a reversible process: an electron and hole be excited by a photon, and they can recombine and emit a photon too.)

- This process of creating electrons (and holes) with photons, changes the semiconductor electrical conductivity too. So the process is often called "photoconductivity" or "photoresistivity"



Semiconducting Light Detectors (cont)

Candidate Photoconductors

Material	Band gap (eV)	λ_{max} (µm)
SiC	2.0–7.0	~0.2–0.6
C (diamond)	5.5	0.22
BN	5.0	0.25
NiO	4.0	0.31
ZnS	3.6	0.34
GaN	3.4	0.36
ZnO	3.3	0.37
CdS	2.41	0.52
CdSe	1.8	0.69
CdTe	1.5	0.83
GaAs	1.43	0.86
Si	1.12	1.10
Ge	0.67	1.85
InAs	0.35	3.54
PbTe	0.3	4.13
PbSe	0.27	4.58
InSb	0.18	6.90
$Hg_{0.83}Cd_{0.17}Te$	0.11	11.0

Ultraviolet (SiC – ZnO)

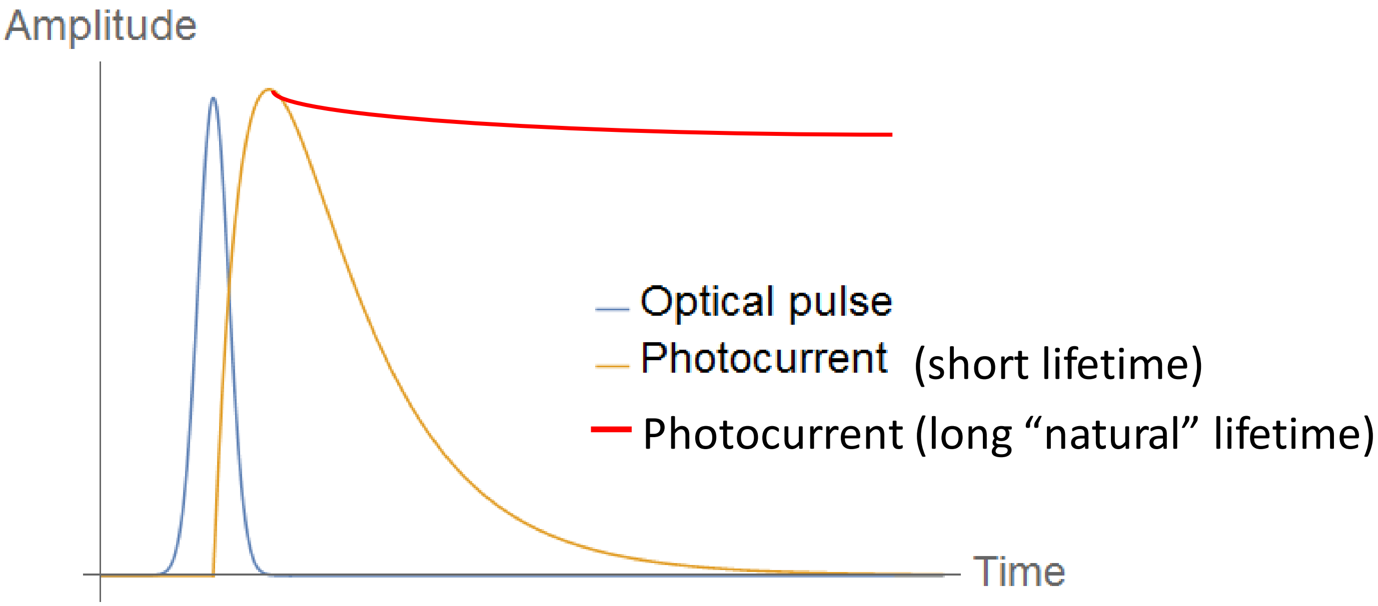
Visible (CdS – CdSe)

Infrared (CdTe – $Hg_{0.83}Cd_{0.17}Te$)

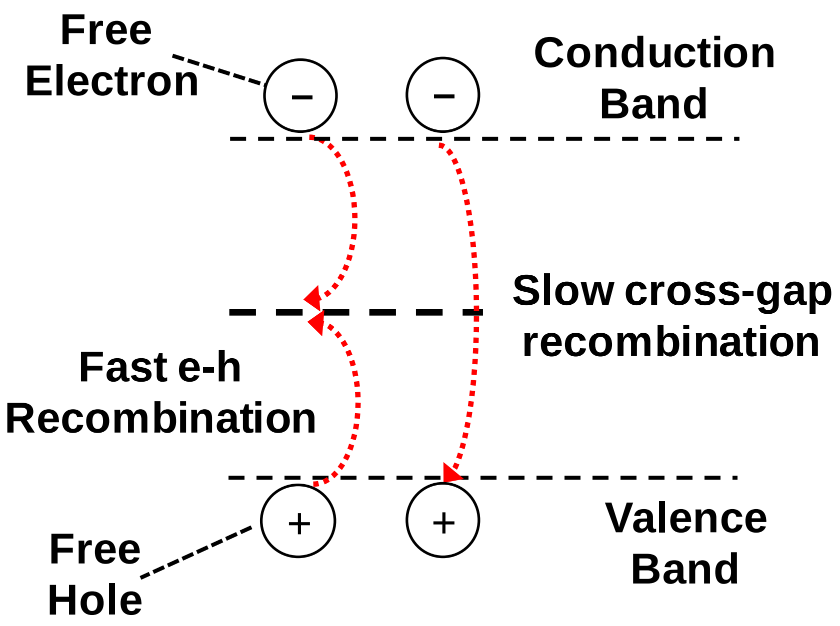
Reducing the Photocarrier Lifetime

- The lifetime limits the speed-of-response for photoconductors. The "natural" lifetime is where electrons and holes recombine by emitting a cross-gap photon.
- Natural lifetime is typically ~1 ns in direct-gap semiconductors (e.g. GaAs); much longer for indirect bandgap semiconductors (e.g., Si).

Optoelectronic Response Function



Speeding Up Photocarrier Recombination



Reducing the Photocarrier Lifetime

- **The most popular technique is to introduce defects that create a high density-of-states near mid-gap of the host semiconductor. There are two types of defects:**

(1) Induced defects:

(a) Ion-implant heavy atoms like Ar. This was done early with Si substrates.

(b) Heavy doping of a metallic species, like As or Er.

(2) Spontaneous defects:

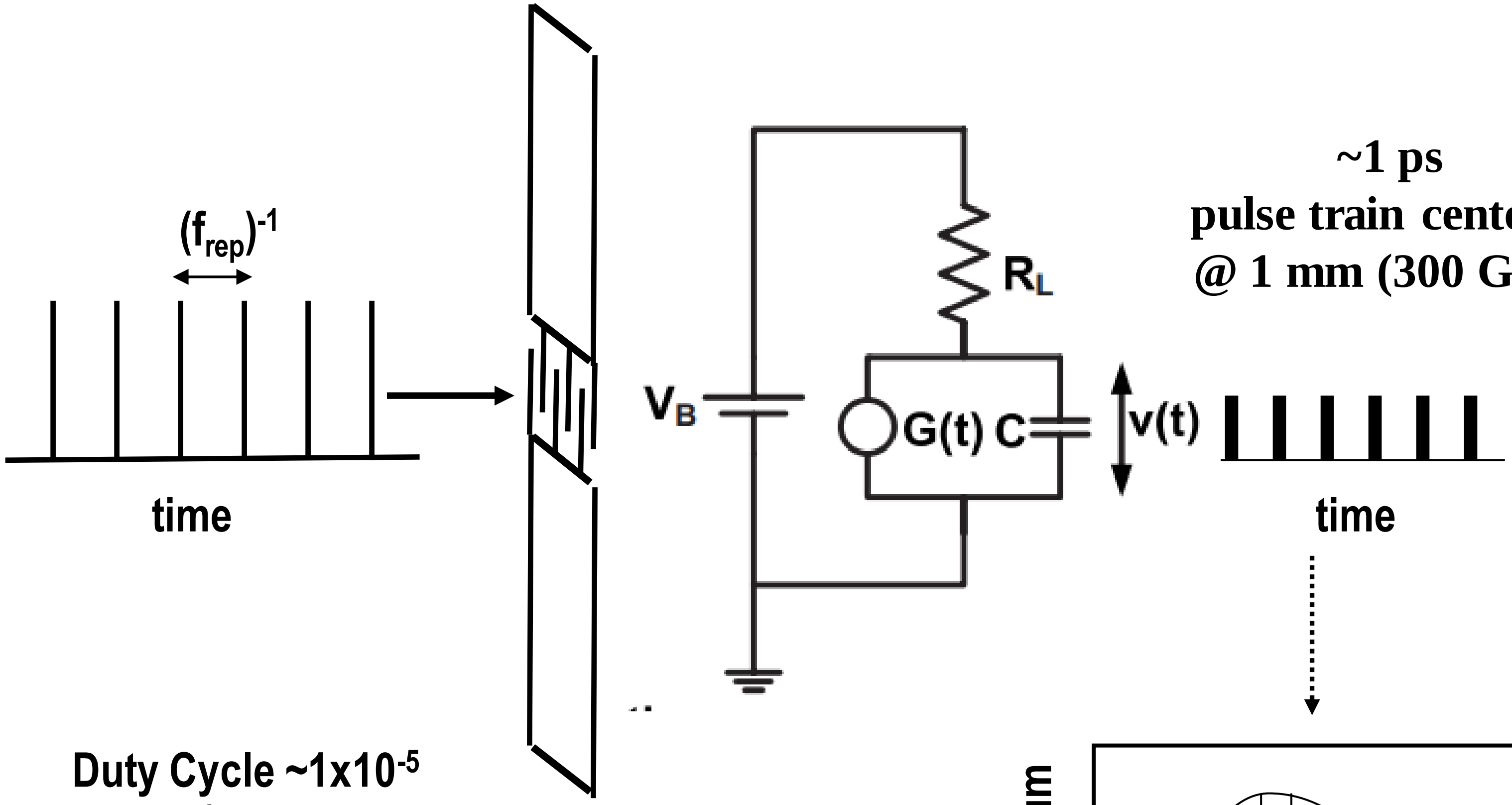
(a) Low-temperature growth

(b) Lattice-mismatched growth

- ***The goal is to greatly decrease the photocarrier lifetime with minimum impact on the photocarrier mobilities (this is not an easy thing to do).***

Photoconductive Switch as THz Source

t_P~100 fs
pulse train
centered
@ λ_0
$P_{peak} >> P_0$

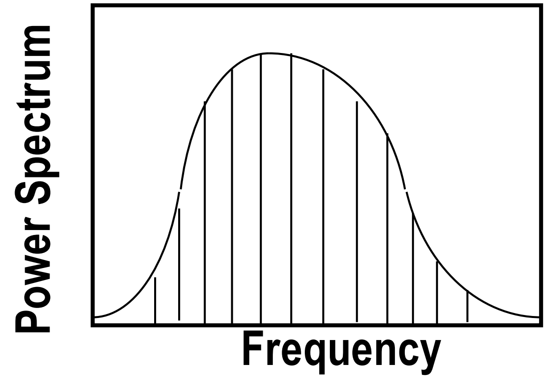


~1 ps
pulse train centered
@ 1 mm (300 GHz)

Duty Cycle ~1x10^{-5}

$$\text{THz: } P_{ave}^{max} \sim \frac{(V_B)^2}{R_L} f_{rep} \cdot t_P \quad \text{for } P_{peak} \approx 100 \text{ W}$$

$$P_0 \sim P_{peak}\,(f_{rep} \cdot t_P) \sim 1 \text{ mW}$$



First THz Photoconductive Device

Antenna-Coupled Photoconductive Gap

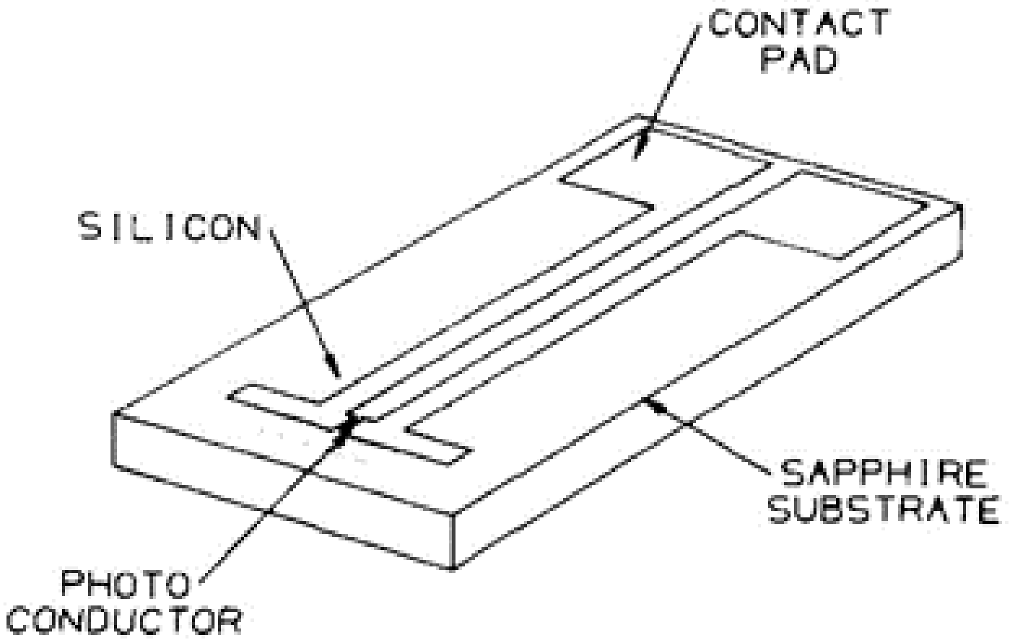


Fig. 1. Antenna structure consisting of the dipole, photoconductor, contact pads, and coplanar strip transmission line between photoconductor and contact pads. The carrier relaxation time of the silicon was reduced by using radiation damage with a dose of 3×10^{15} cm^{-2} 2 MeV Ar^{+} ions at room temperature.

D. H. Auston, K. P. Cheung and P. R. Smith, "Picosecond photoconducting Hertzian dipoles", Appl. Phys. Lett., vol. 45, no. 3, pp. 284-286, Aug. 1984.

First THz Photoconductive System

First Transmitter-Receiver Combination (Time-Domain Transceiver)

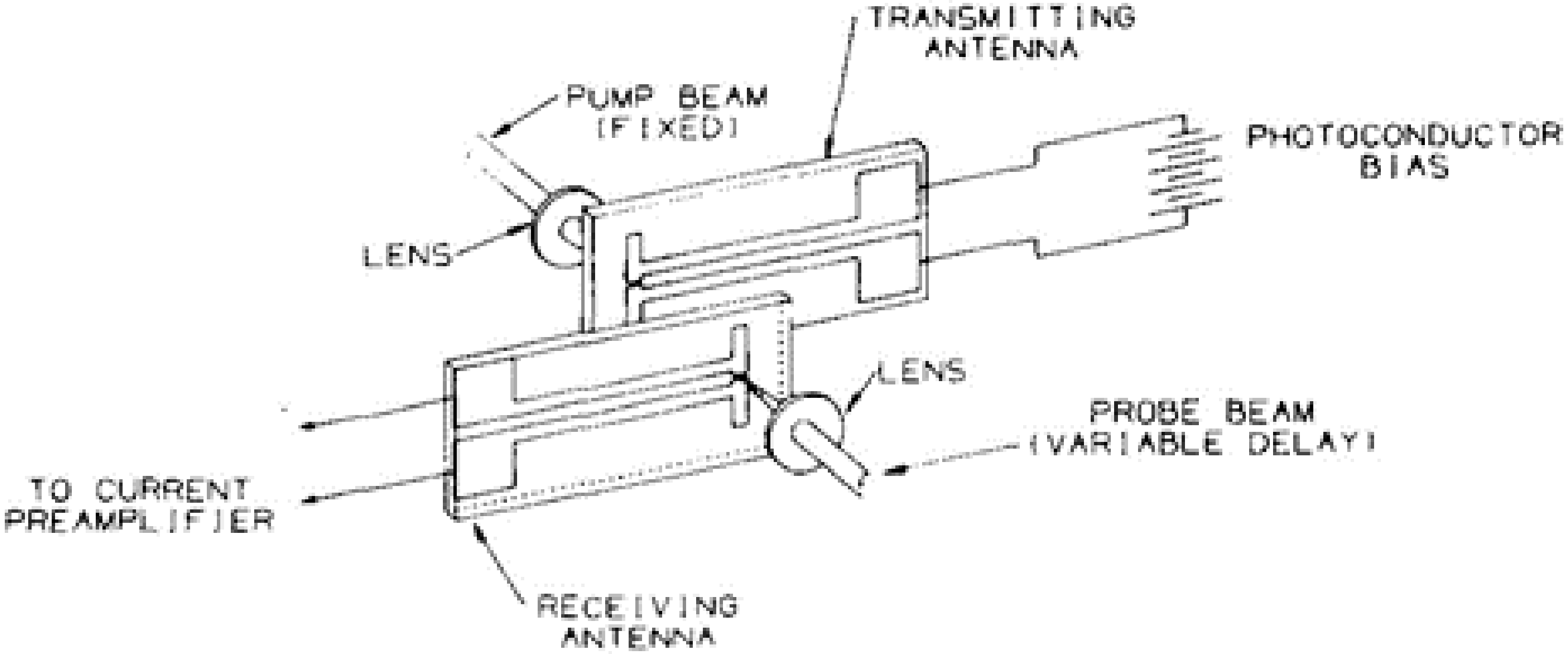
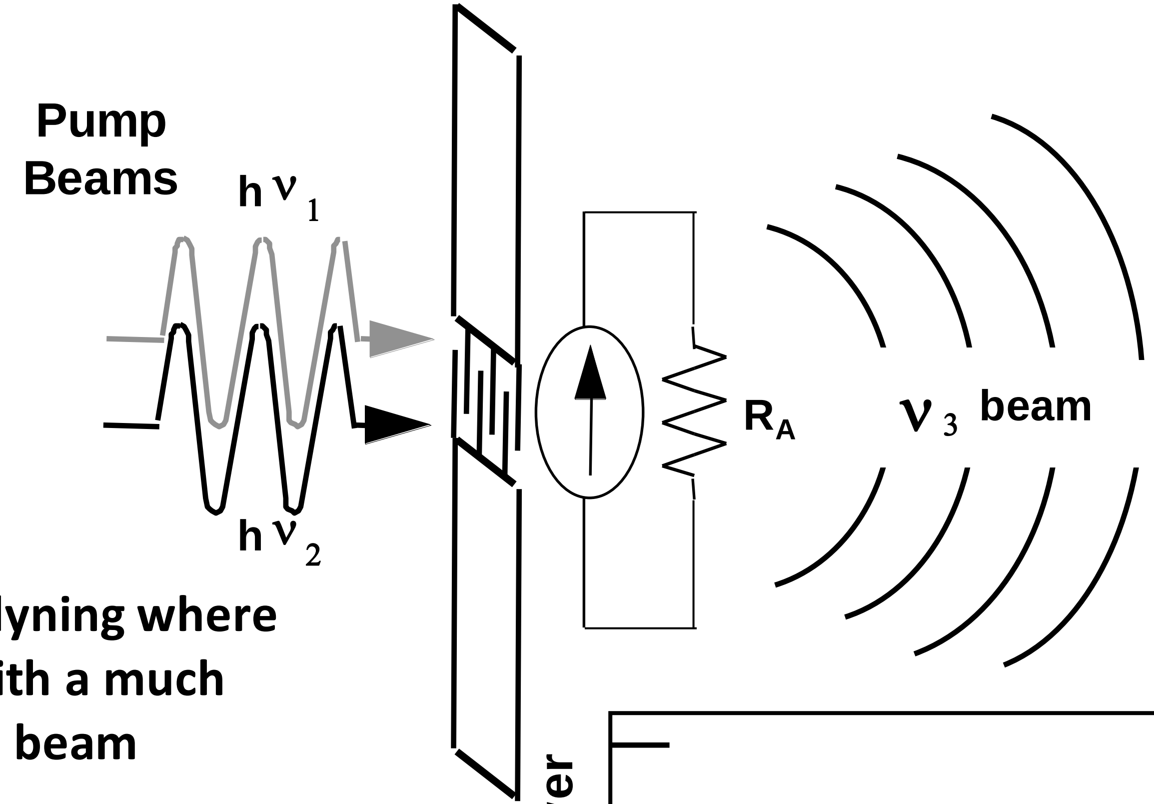


Fig. 2. Diagram of experimental setup. Substrate surfaces with the antennas are facing each other. The photoconductors are collinear with the optical beams which illuminate through the substrate from the back. Separation between the antennas is 2 mm.

P. R. Smith, D. H. Auston and M. C. Nuss, "Subpicosecond photoconductive dipole antennas", IEEE J. Quantum Electron., vol. 24, no. 2, pp. 255-260, Feb. 1988.

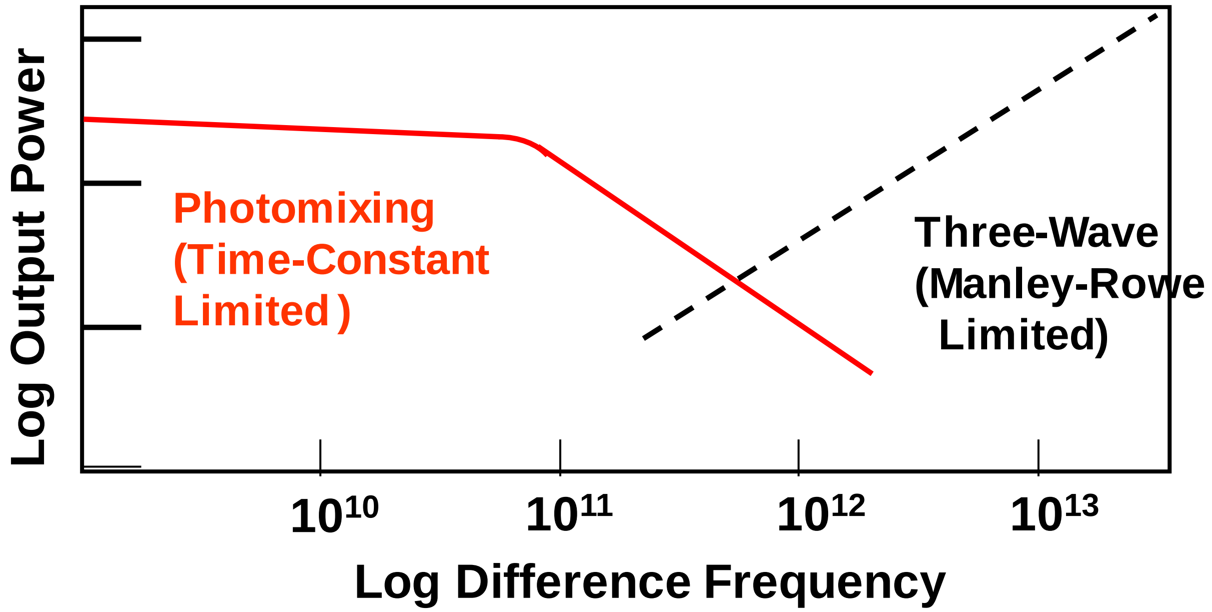
Photoconductive Mixing (Photomixing) as THZ Source



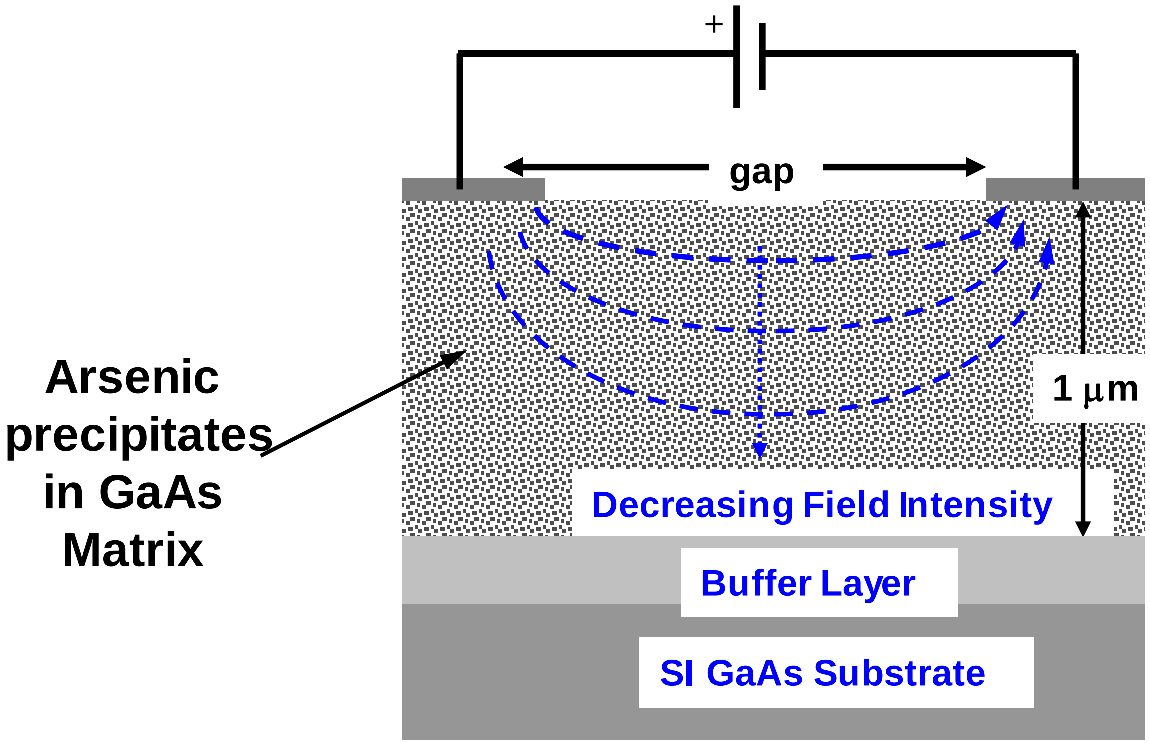
$\nu_3 = |\nu_2 - \nu_1|$

More challenging than PC switching because of spatial coherence requirement of two beams, greater thermal stress, etc.

- **Similar to optical heterodyning where a small signal is mixed with a much stronger (local oscillator) beam**
- **But in photomixing, the two "pump" beams should have the same power**
- $I_P = A \cdot P_0 = B \cdot (E_0)^2 = C \cdot (E_1 \cdot E_1)^2$ ***where A, B, and C are constants, and E_1 E_2 the frequency-offset optical electric fields.*** **(perfectly quadratic generation function)**



Breakthrough Material: Low-Temperature-Grown (LTG) GaAs (circa 1990)

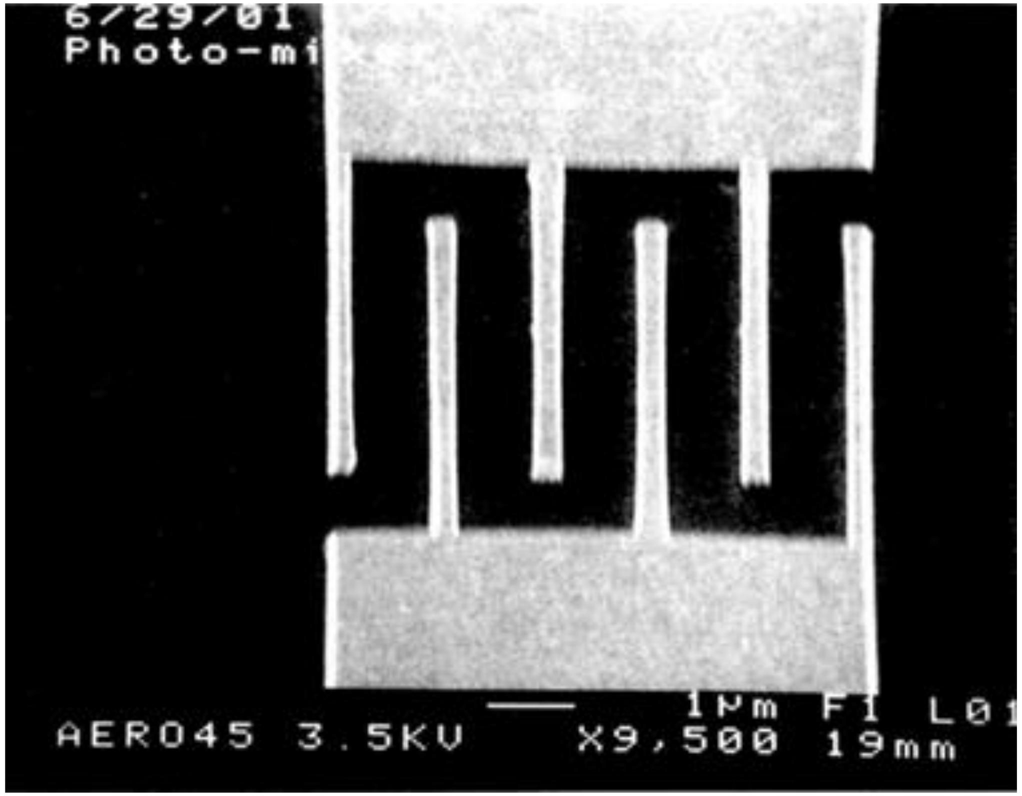


To get electron-hole lifetime << 1 ps:

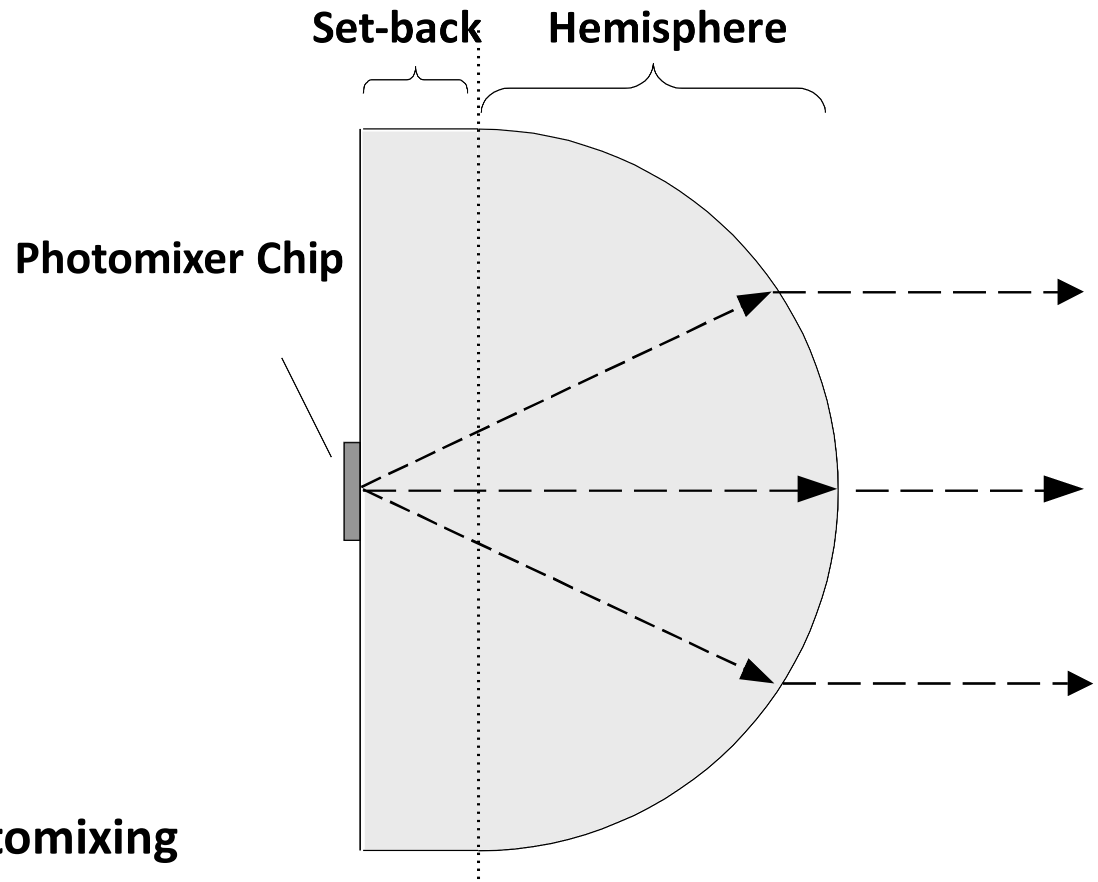
- Grow by MBE at ~200°C or less; yields non-stoichiometric mix of ~1% excess arsenic
- Follow growth by high-temp anneal (>500°C) in arsenic-rich environment
- But, growth temperature of ~200°C is difficult to control and reproduce

Technological Leverage

Submicron Interdigital Electrodes

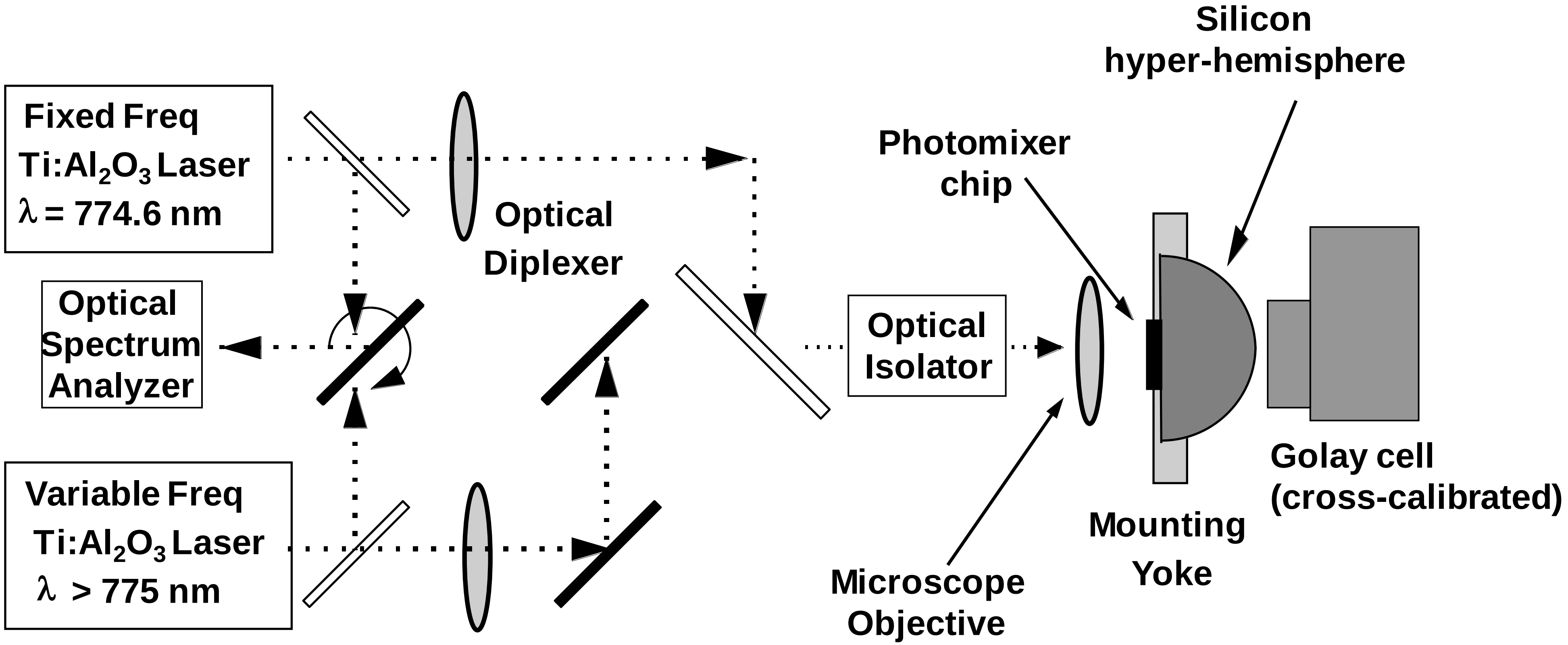


High-Resistivity Si and GaAs Optics



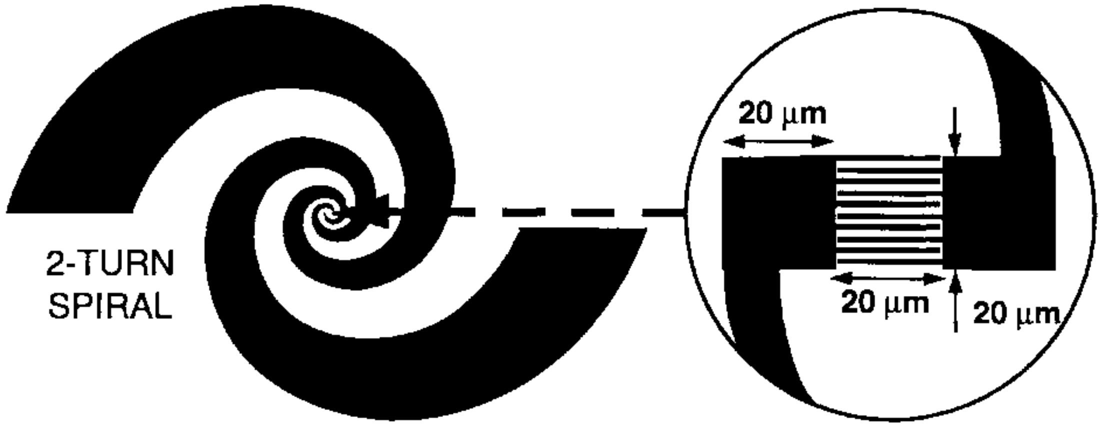
Interdigital Electrodes greatly increase the THz photomixing power compared to a simple gap, but have greater capacitance so contribute to the frequency rolloff of the device.

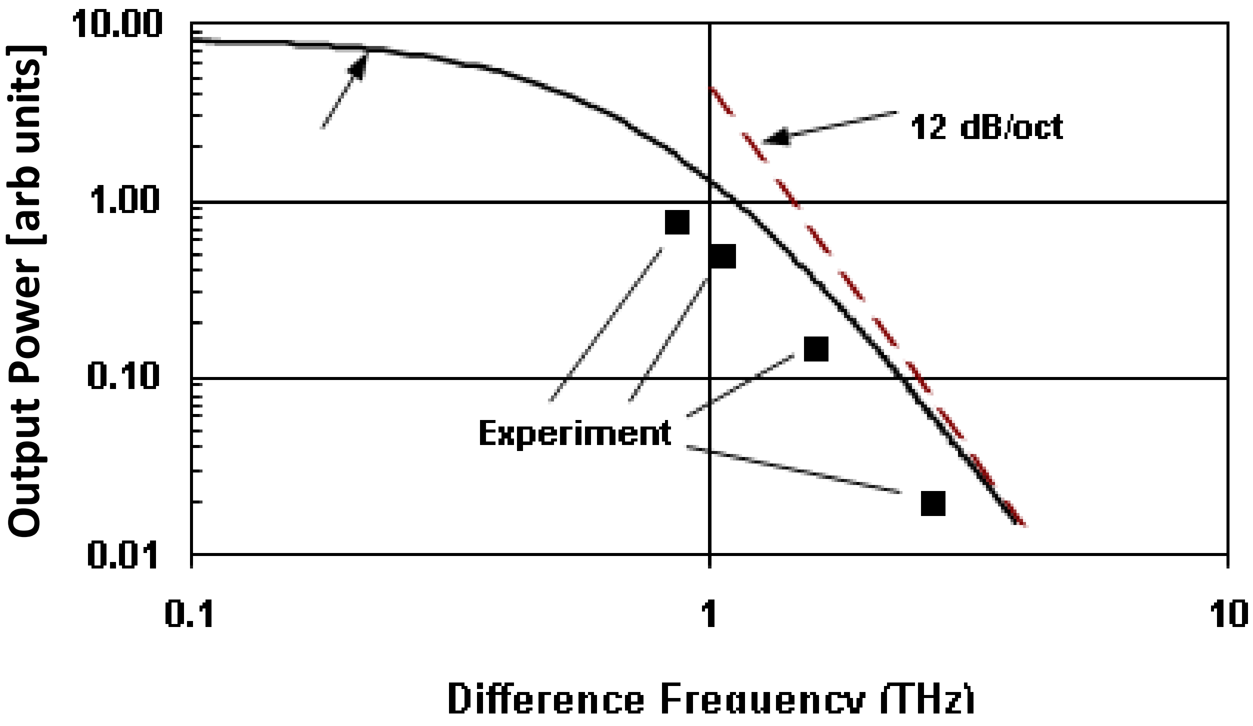
Experimental Set-Up



First THz Photomixer Study

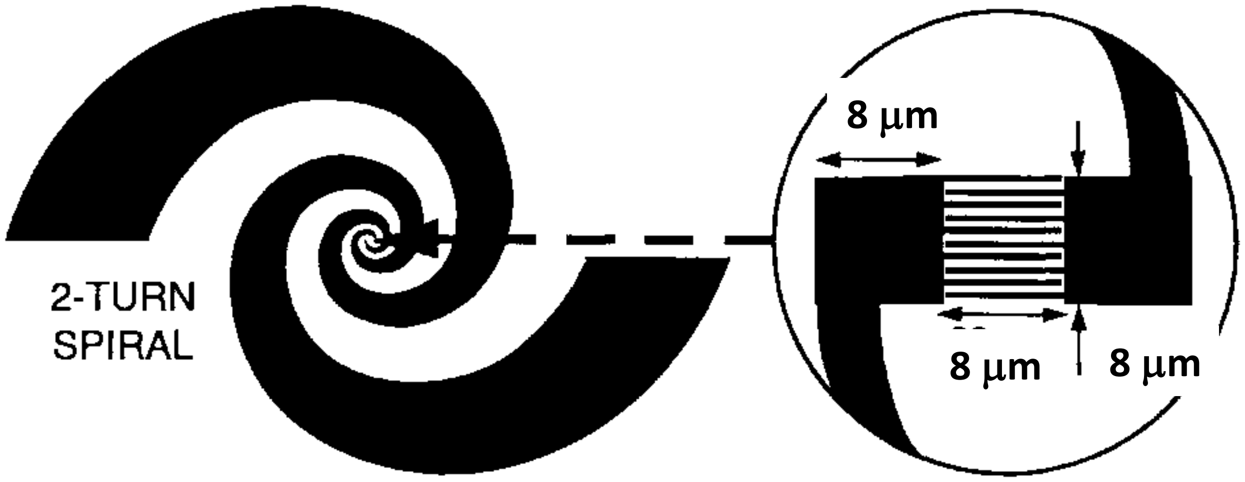
(two Ti:Al_2O_3 pump lasers, one LTG-GaAs photomixer)

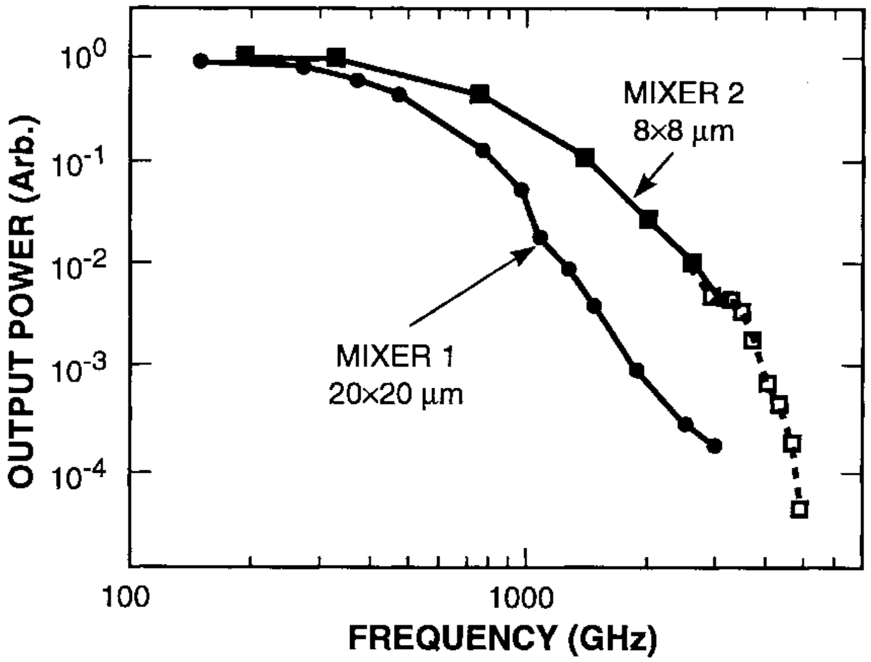




"Photomixing up to 3.8 THz in low-temperature-grown GaAs," E.R. Brown, K.A. McIntosh, K.B. Nichols, and C.L. Dennis, Appl. Phys. Lett., vol. 66, p. 285 (1995)

Effect of Device Capacitance



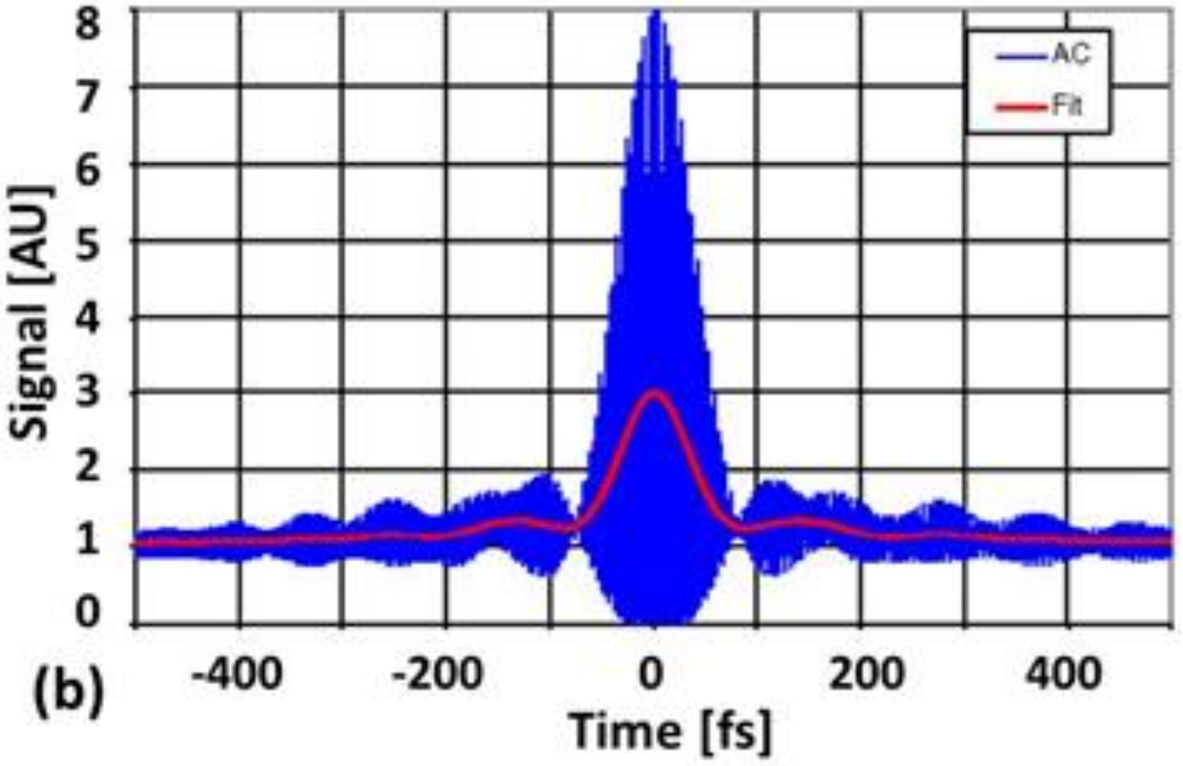


"Highly tunable fiber-coupled photomixers with coherent THz output power," S. Verghese, K. A. McIntosh, and E. R. Brown, IEEE Trans. Microwave Theory and Tech, vol. 45(8), pp. 1301-1309 (1997).

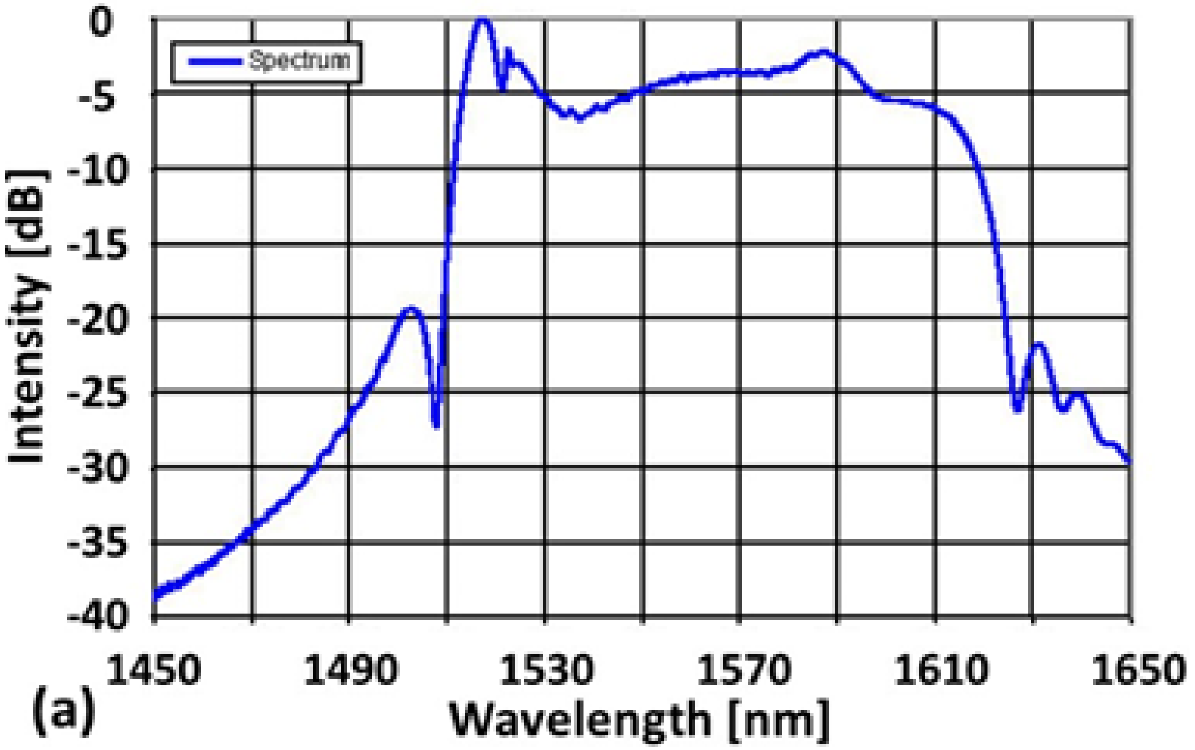
The Race to ~1550-nm THz Devices: Pulsed Operation

- **Erbium-doped fiber-amplifier (EDFA) mode-locked lasers**

EDFA Single-Pulse Characteristics (by autocorrelation)

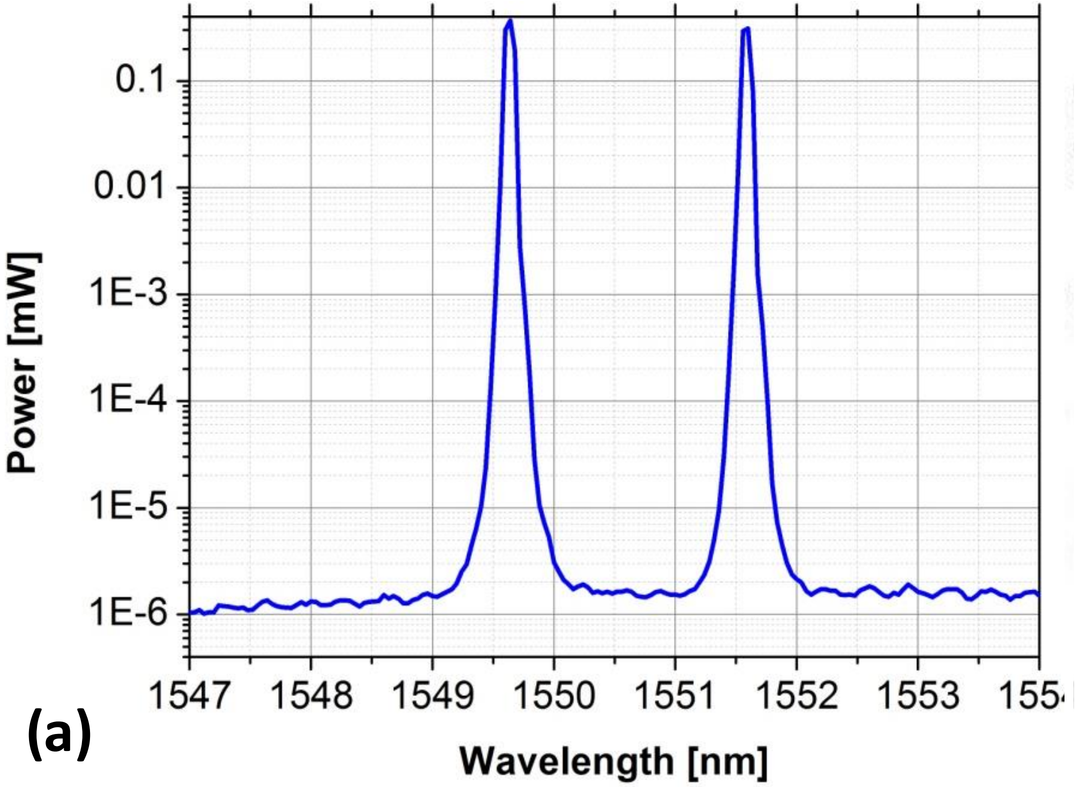


Single-Pulse Power Spectrum (by OSA)

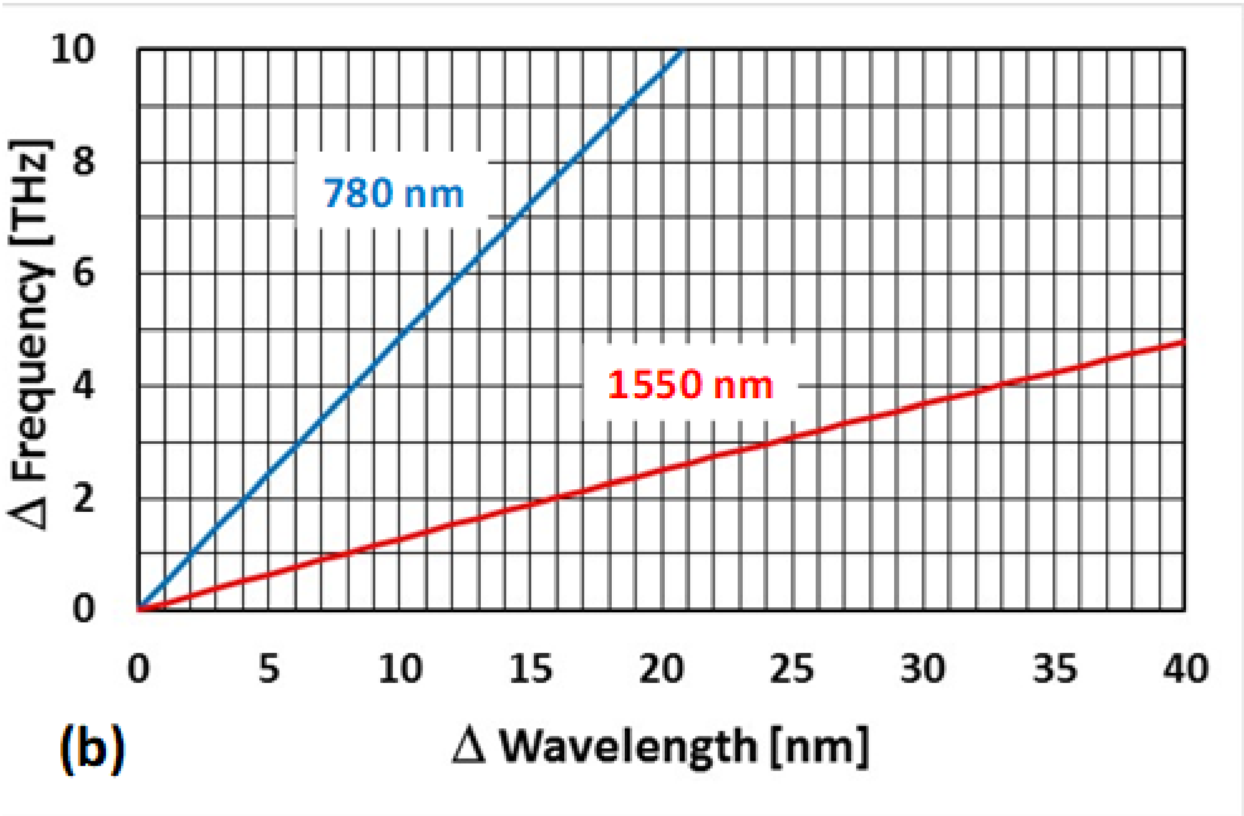


The Race to ~1550-nm THz Devices: CW Operation

Two Frequency-Offset Distributed Feedback (DFB) Diode Lasers



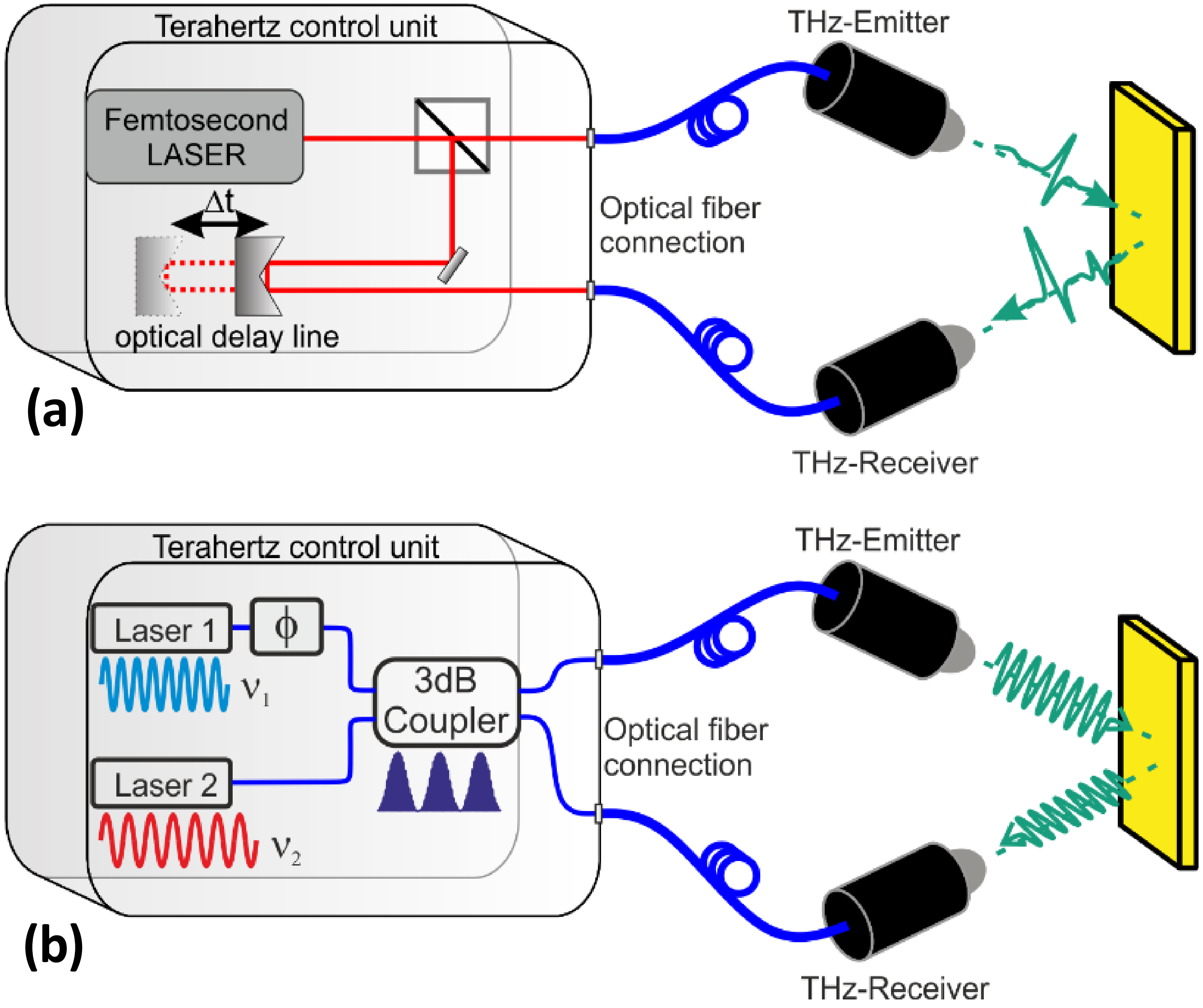
Dual DFB Laser Tuning Curve



- DFB lasers are single-frequency, single-mode output
- Simple to tune by temperature control.

- Approximately twice as many photons/W at 1550 nm as at 780 nm.
- At 1550 nm, tuning range is limited to ~ 2 THz.

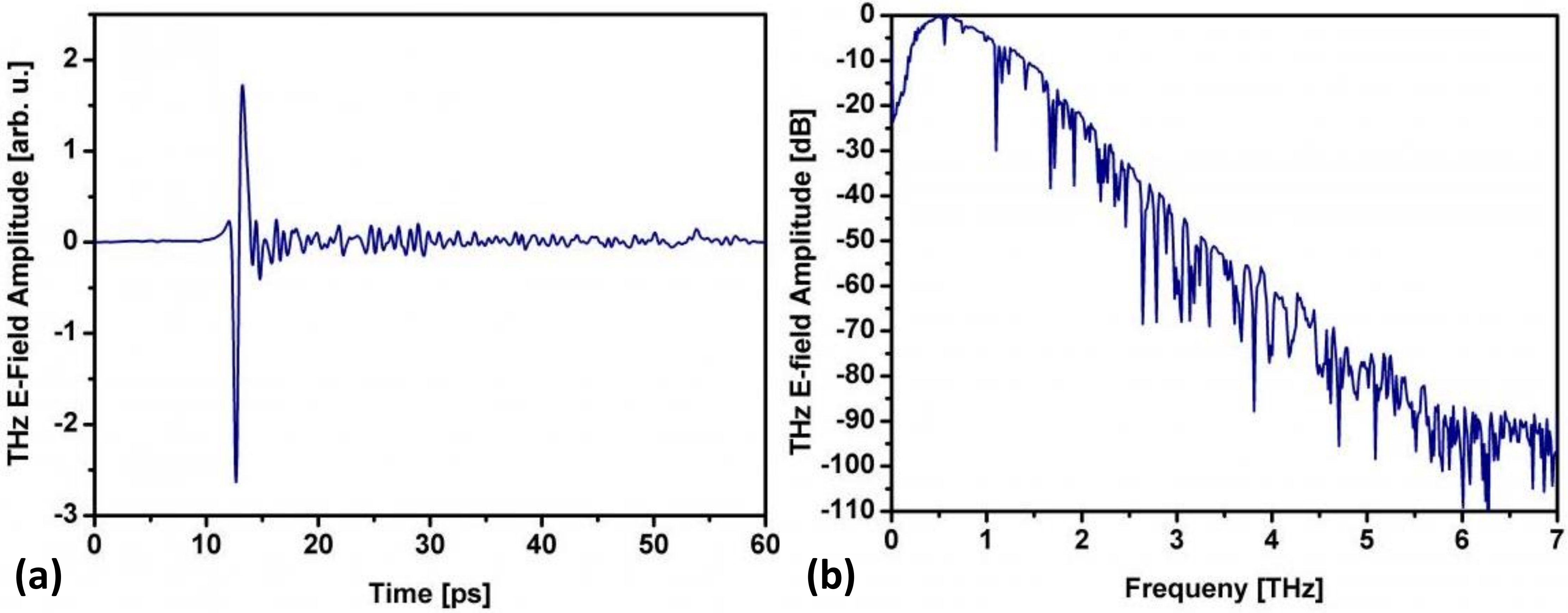
Another 1550-nm Advantage: Fiber Coupling



InGaAs-on-InP Materials for 1550-nm Operation

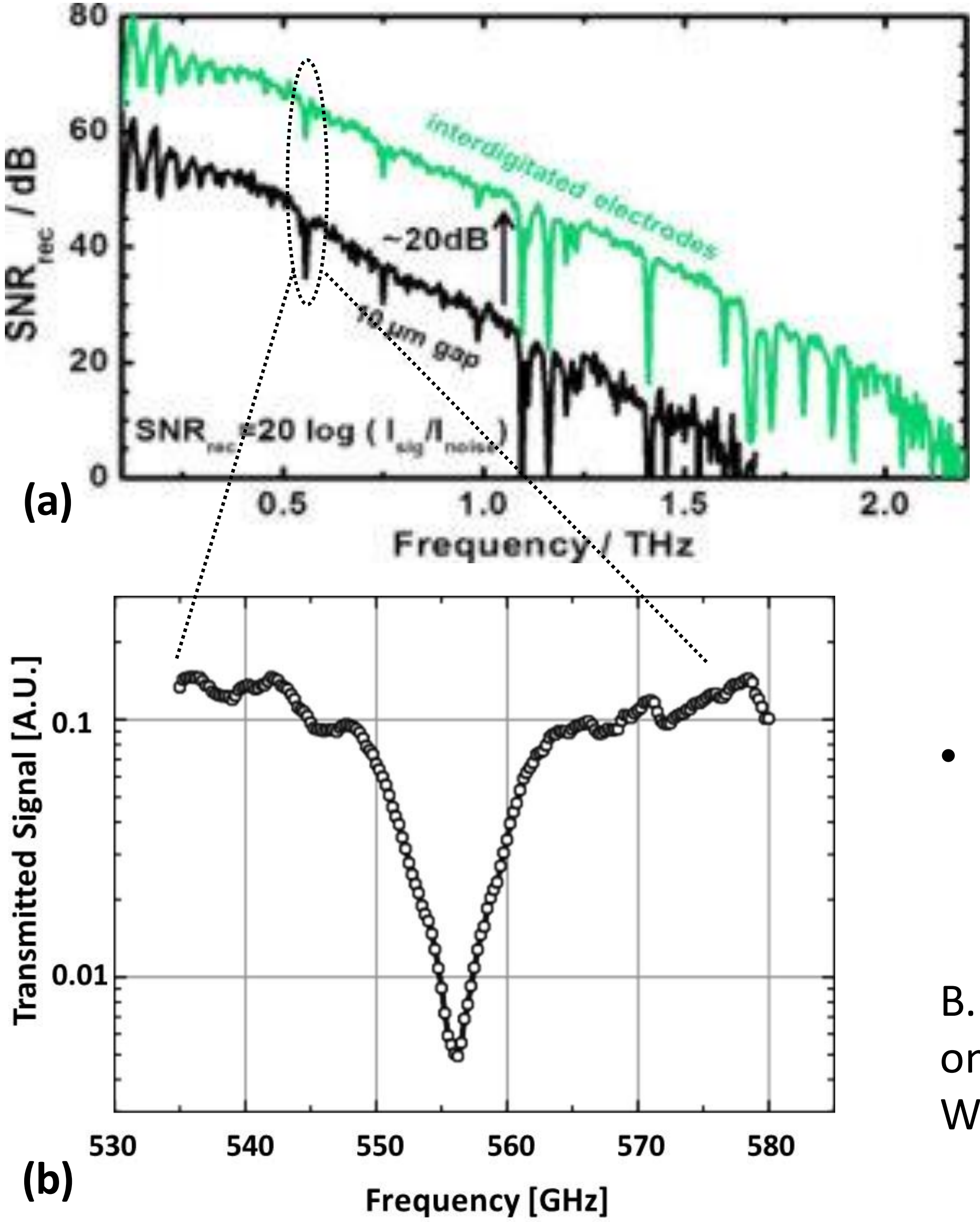
Material	Carrier lifetime (ps)	Mobility (cm^2/Vs)	Resistivity (Ω.cm)	Reference
Be-doped LTG InGaAs	0.35	100	700	A. Takazato et al., Appl. Phy. Lett. 90, 10119 (2007)
Fe-implanted InGaAs	0.3	1500	1000	C. Camody et al., Appl. Phys. Lett. 82, 3919 (2003)
ErAs:InGaAs	0.2	490	340	D. C. Driscoll et al., Appl. Phys. Lett., 86 051908 (2005)
Br-irradiated InGaAs	0.2	490	3	N. Chimot et al., Appl. Phys. Lett., 87, 193510 (2005)
Be-doped LTG InGaAs/InAlAs	1	1900	1.2×10^5	B. Sartorius et al., Optics Exp. 16, 9565 (2008)
Cold-implanted InGaAsP	0.3	400	1200	A. Fekecs et al., Opt. Mat. Exp. 1, 1165 (2011)

State-of-the-Art 1550-nm PC Switch



https://www.menlosystems.com/assets/datasheets/THz-Time-Domain-Solutions/MENLO_TERA_K15_D-EN_2020-05-11_3w.pdf

InGaAs Photomixer Results

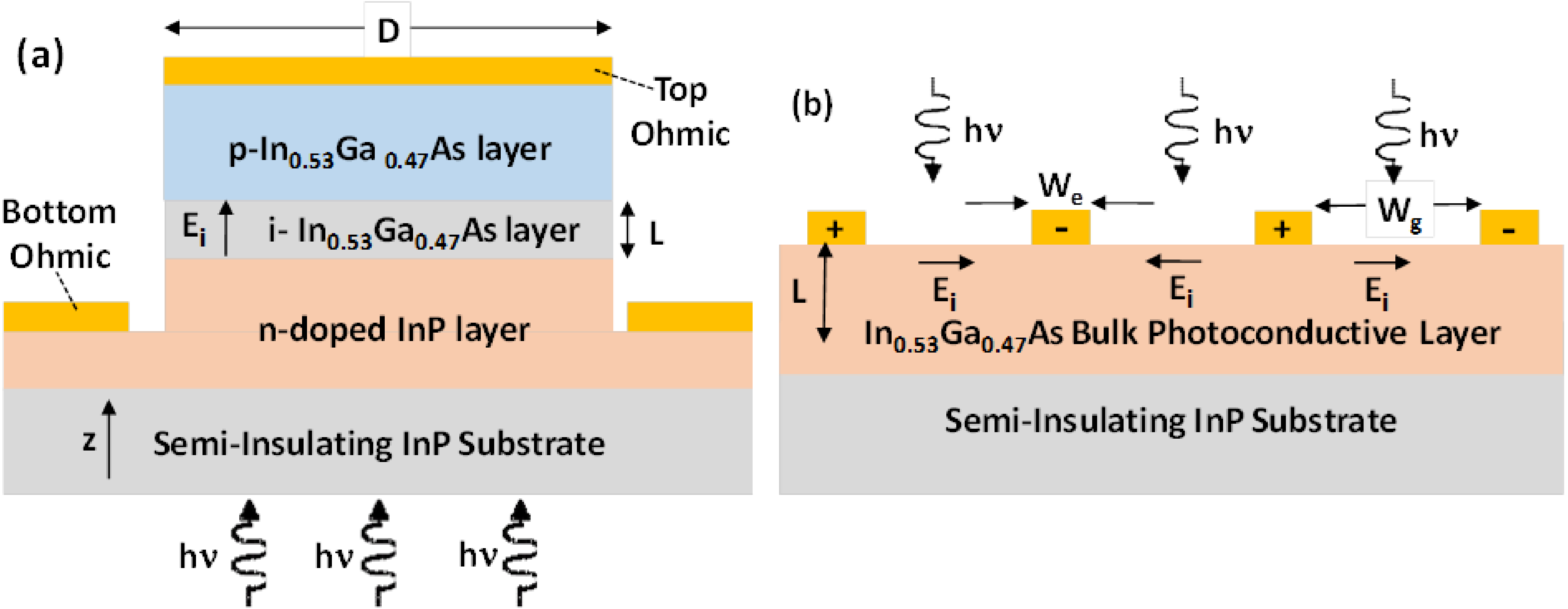


- **Full tuning (limited by DFB temperature range)**

- **Zoom-in on water-vapor line**

B. Sartorius et al., "Continuous Wave Terahertz Systems based on 1.5 μm Telecom Technologies," J. Infrared Milli Terahz Waves, vol. 33, pp. 405-417 (2012).

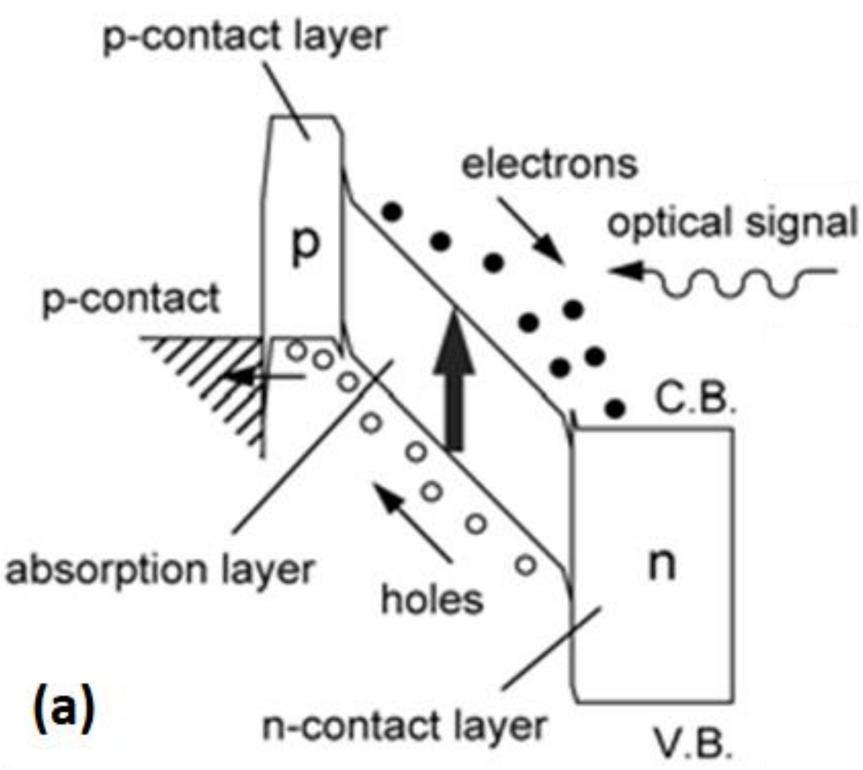
Comparison of InGaAs pin photodiode with MSM Photoconductor



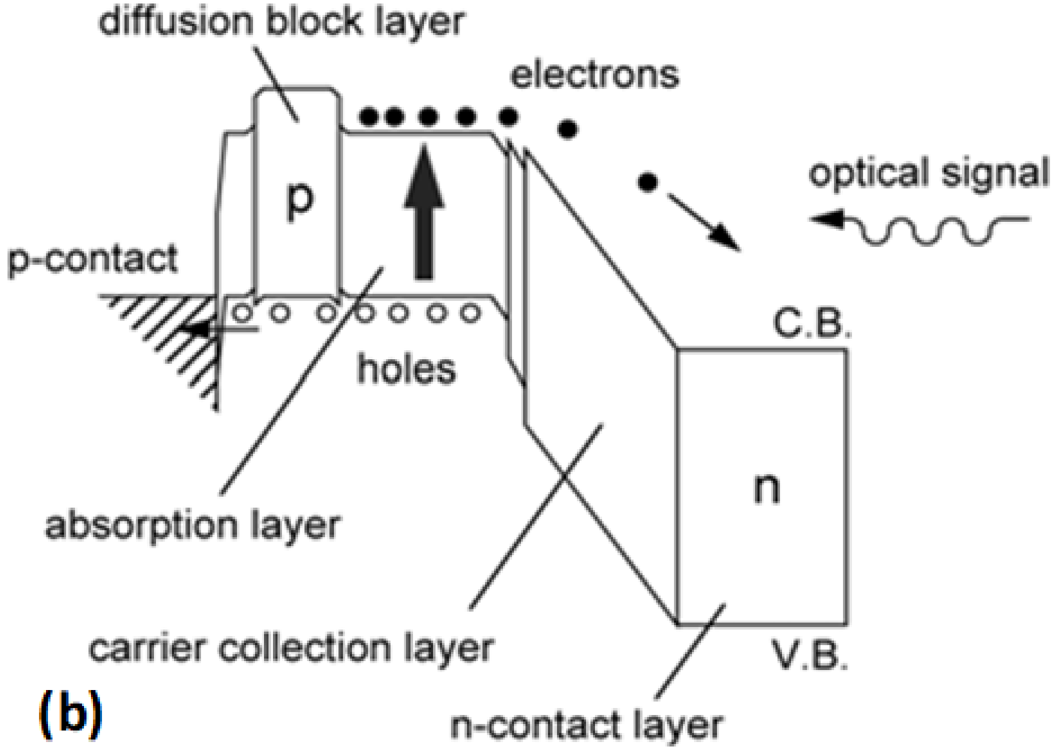
"Photoconductive THz Sources Driven at 1550 nm," E.R. Brown, B. Globisch, G. Carpintero del Barrio, A. Rivera, D. Segovia-Vargas, and A. Steiger, in *Fundamentals of Terahertz Devices and Applications*, ed. by D. Pavlidis (John Wiley and Sons, Inc., W. Sussex, UK, 2021).

Types of InGaAs-Based Photodiodes

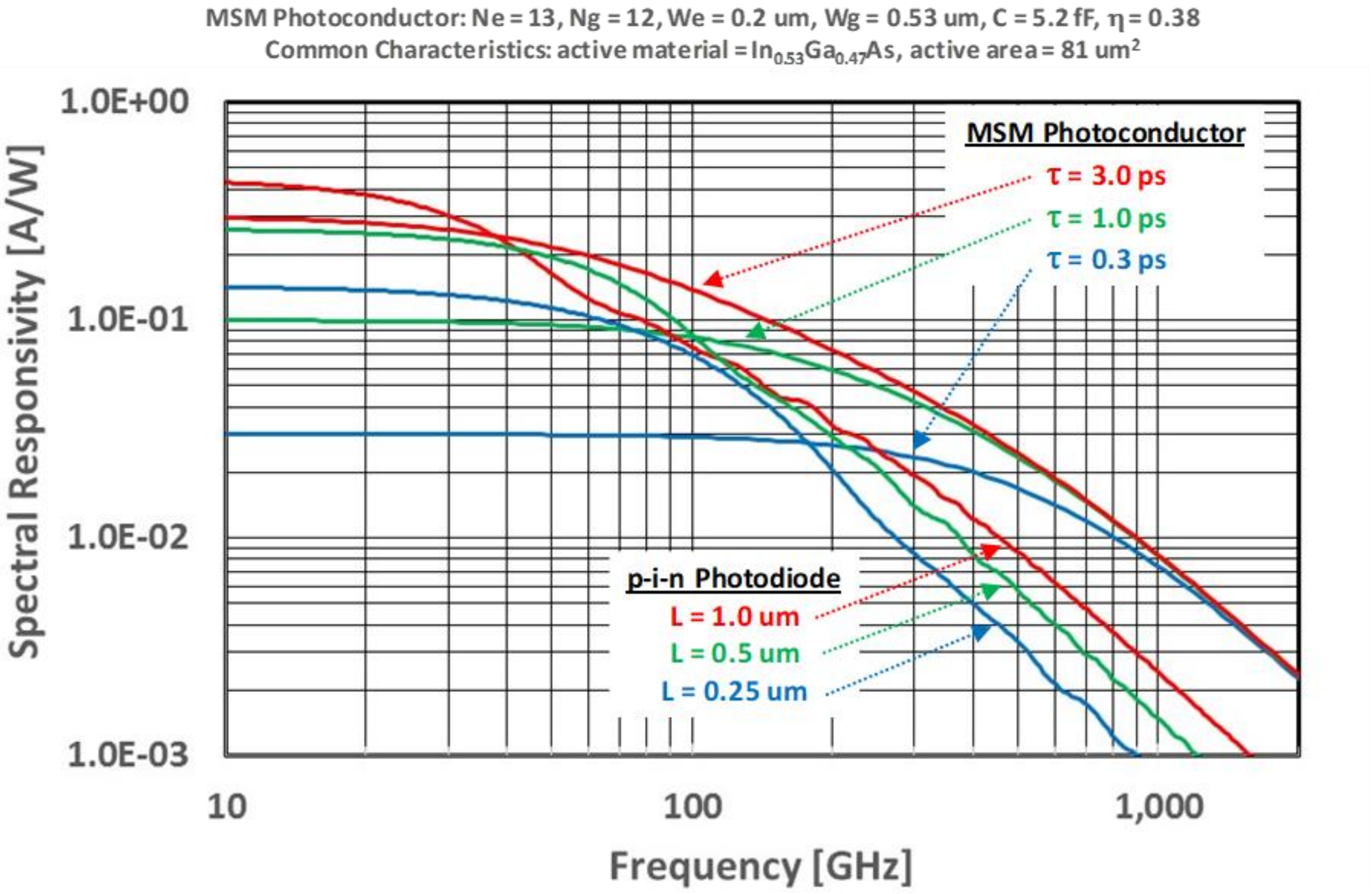
Conventional InGaAs pin Photodiode



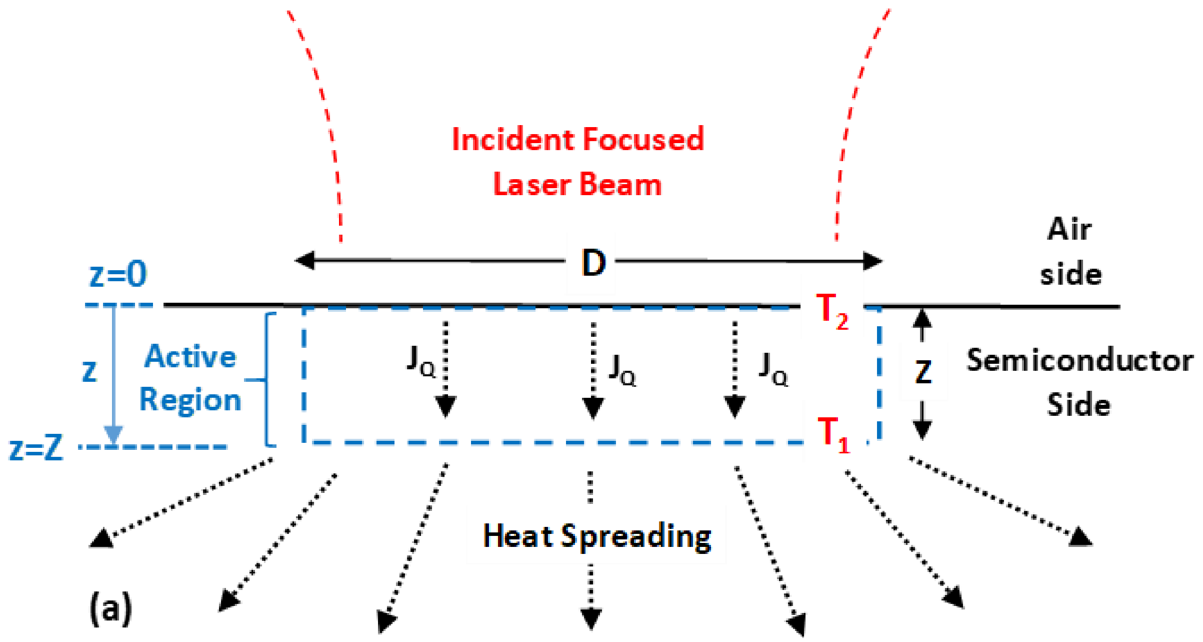
InGaAs UTC Photodiode



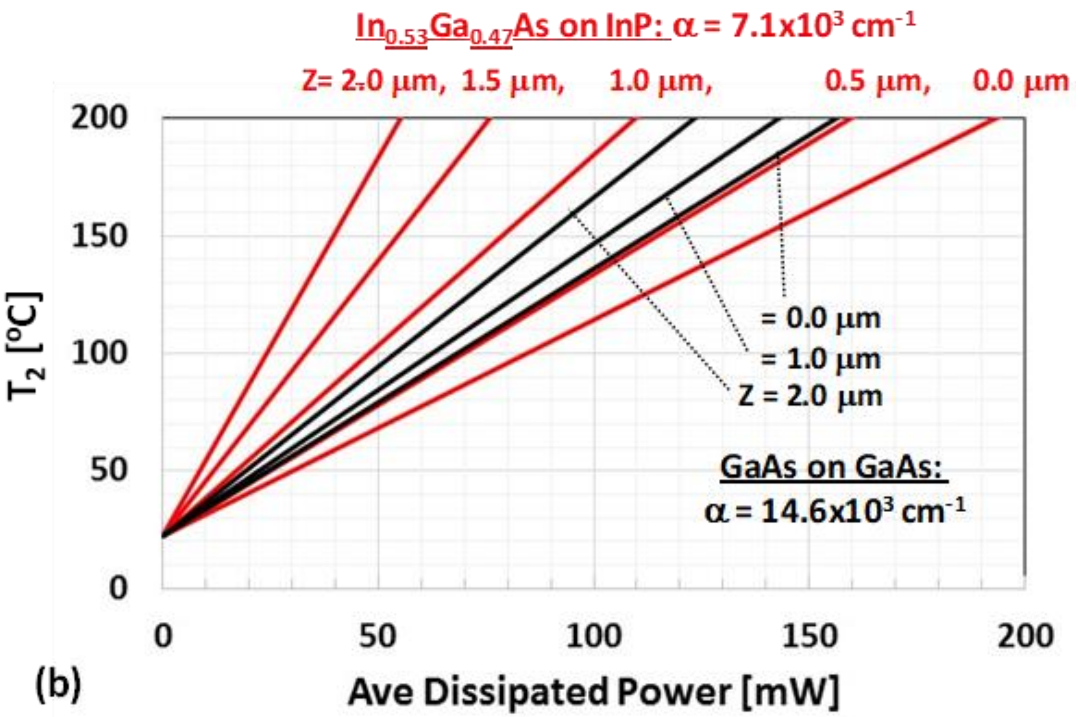
Simulation Results: InGaAs pin photodiode with MSM Photoconductor



Ultimate Limit on THz Photoconductor Generation: Joule Heat



(a)



(b)

Thank You !

Questions ?