GaBiAs epitaxial layers for terahertz optoelectronic applications

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Outline

- Introduction. THz optoelectronic devices.
- GaBiAs: technology and main physical characteristics.
- THz time-domain system based on GaBiAs components.
- THz burst generation by optical mixing.
- Conclusions. Other possible ultrafast applications of GaBiAs components.

Acknowledgements

Vilnius:

Drs.: K. Bertulis, V. Pačebutas, R. Adomavičius.

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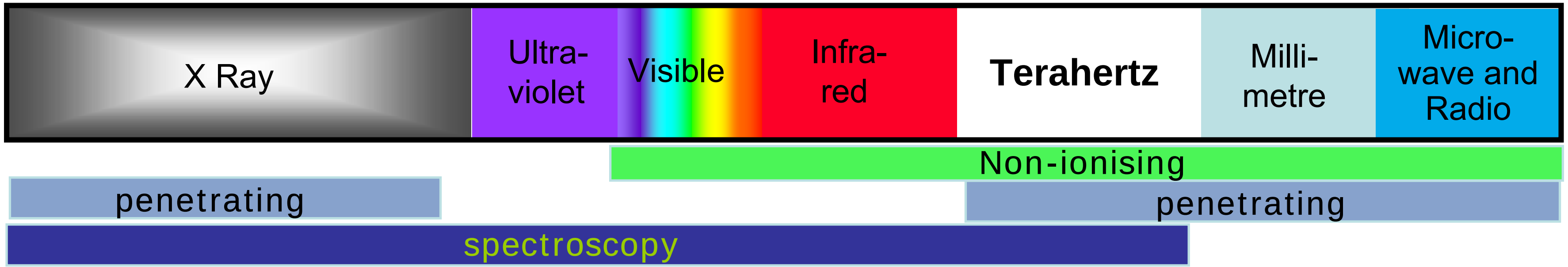
Prof. W. Walukiewicz, Dr. K.M. Yu.

Lithuanian Science & Study Foundation.

Lithuanian Science Council.

THz frequency range

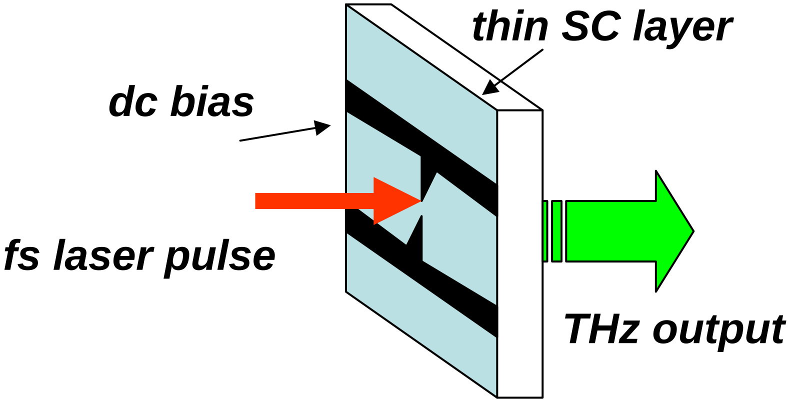


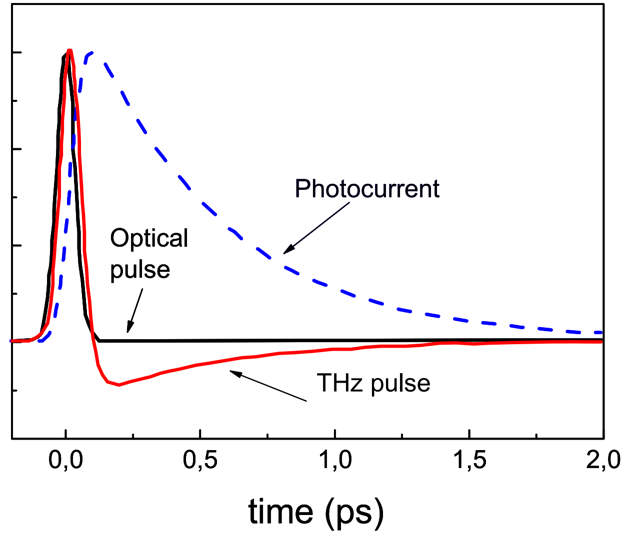
X Ray
Ultra-violet
Visible
Infra-red
Terahertz
Milli-metre
Micro-wave and Radio

Non-ionising
penetrating
penetrating
spectroscopy

- *Key properties:*
  - *Penetrates clothing, leather, paper, plastics, packaging materials.*
  - *Materials identification using characteristic Terahertz spectra.*
  - *3-D imaging capability.*
  - *Non-ionizing - no damage to body or cells*
  - *Short wavelength – high resolution*

THz pulse emission



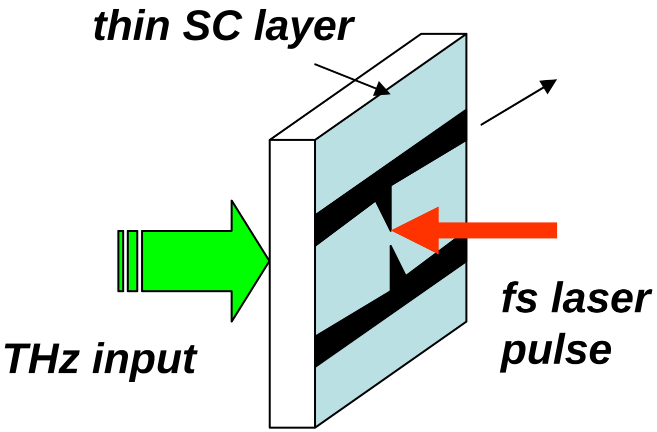


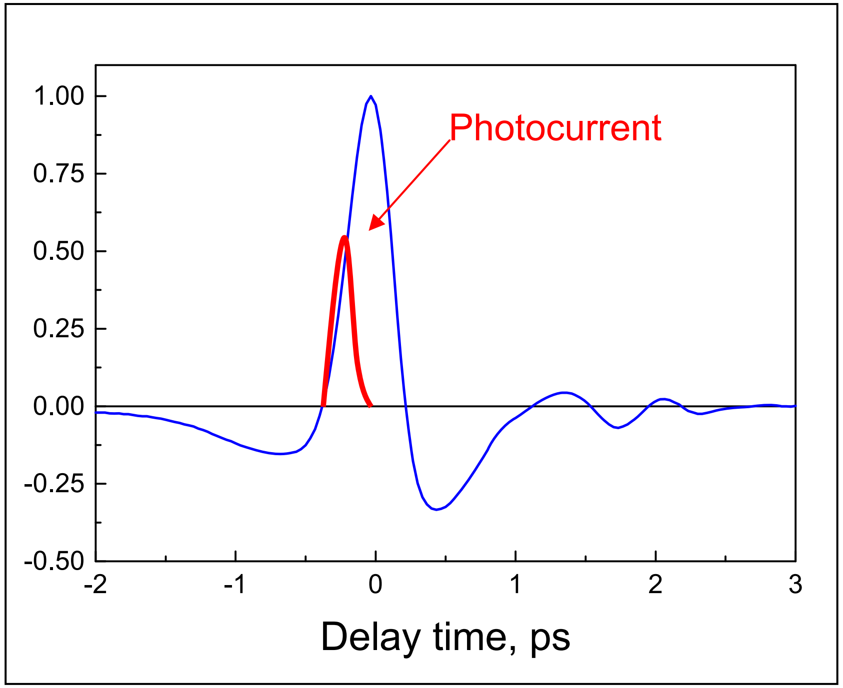
- *Biased photoconductor made from a material sensitive in the fs laser wavelength range;*
- *Contact metallization has the shape of a Hertzian dipole type antenna;*
- *THz pulse is emitted into free space.*

$$\boxed{j_{em}(t) = P(t) \otimes \left[n_{em}(t) q v(t)\right]}$$

$$\boxed{E_{THz}(t) \propto \frac{dj_{em}(t)}{dt}}$$

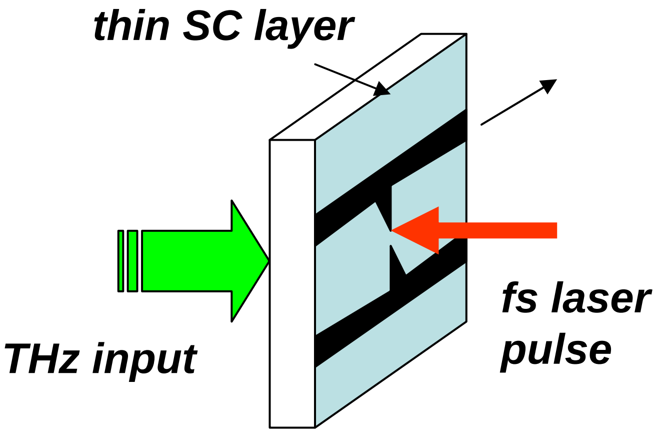
THz pulse detection

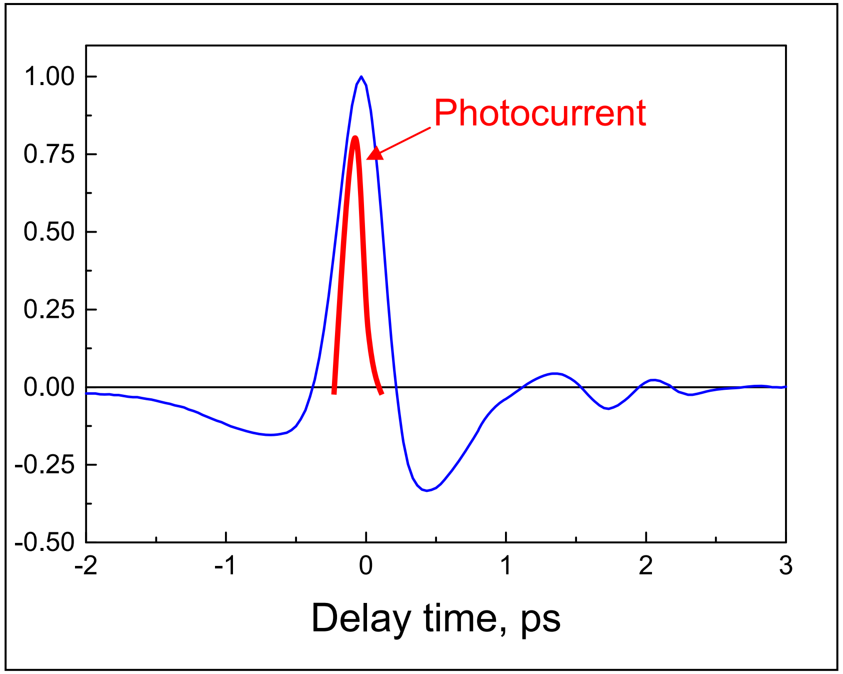




- *Electro-optical and photoconductive detection;*
- *Photoconductor made from material with ultrashort carrier lifetime is biased by the incoming THz pulse;*
- *By illuminating it at different time delays, different parts of THz pulse are sampled;*

THz pulse detection





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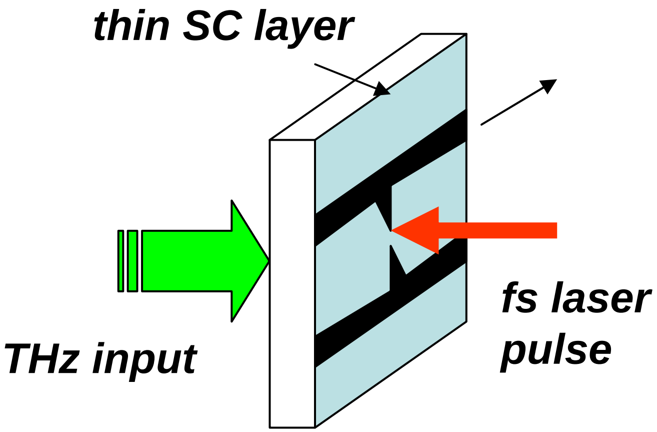
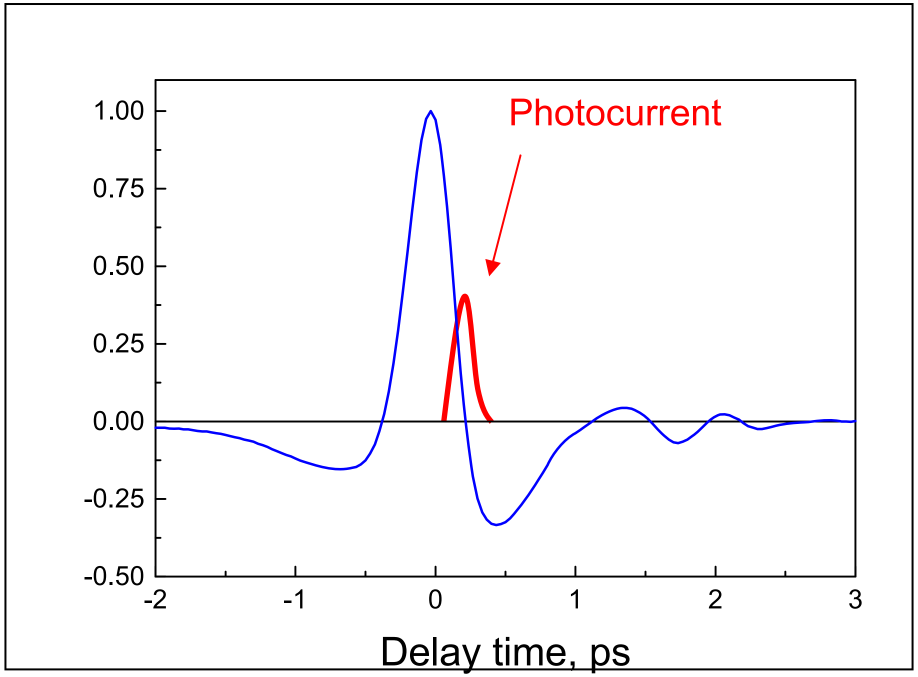
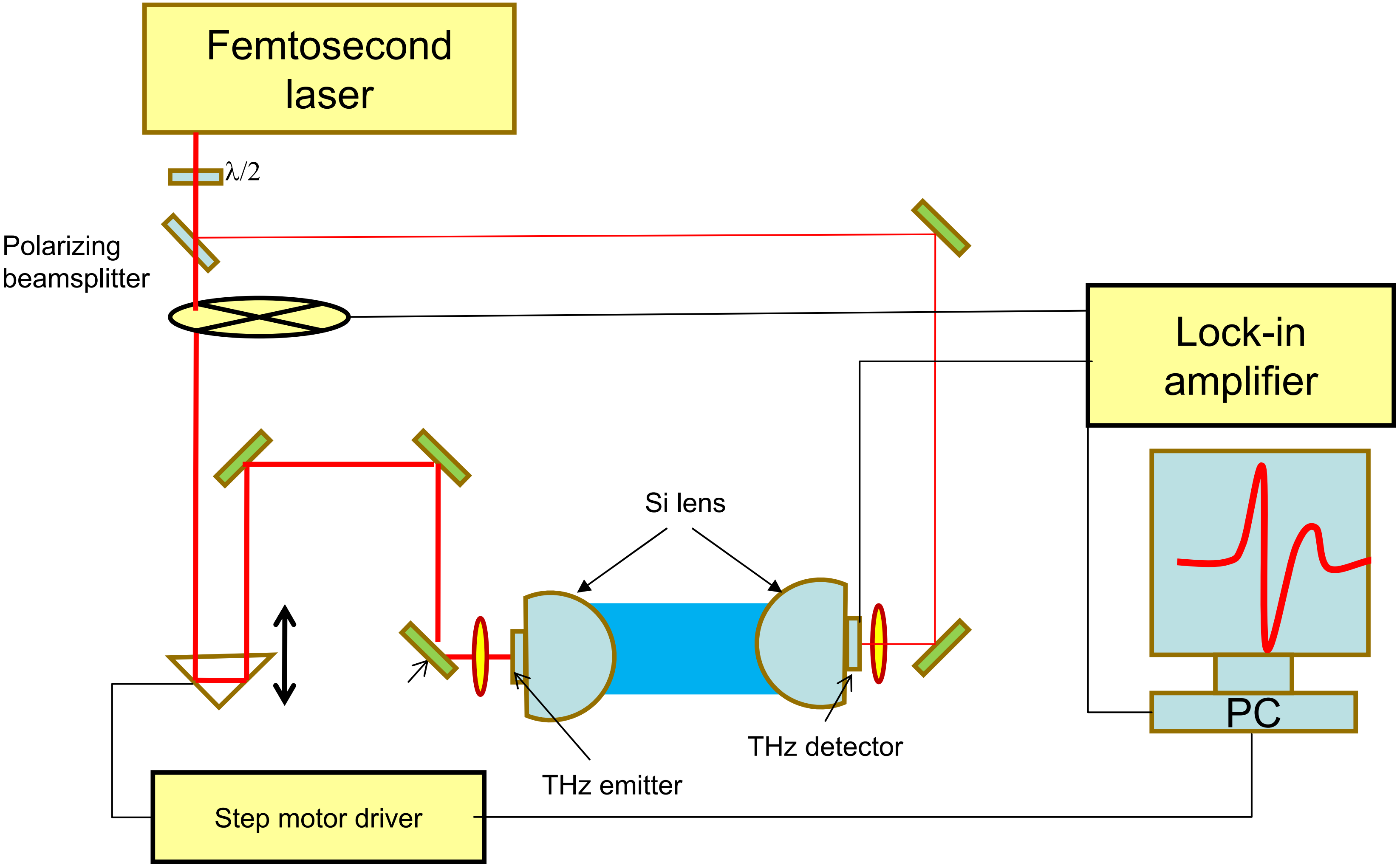
THz pulse detection





- *Electro-optical and photoconductive detection;*
- *Photoconductor made from material with ultrashort carrier lifetime is biased by the incoming THz pulse;*
- *By illuminating it at different time delays, different parts of THz pulse are sampled;*
- ***Critical material parameter – carrier lifetime.***

THz TDS set-up



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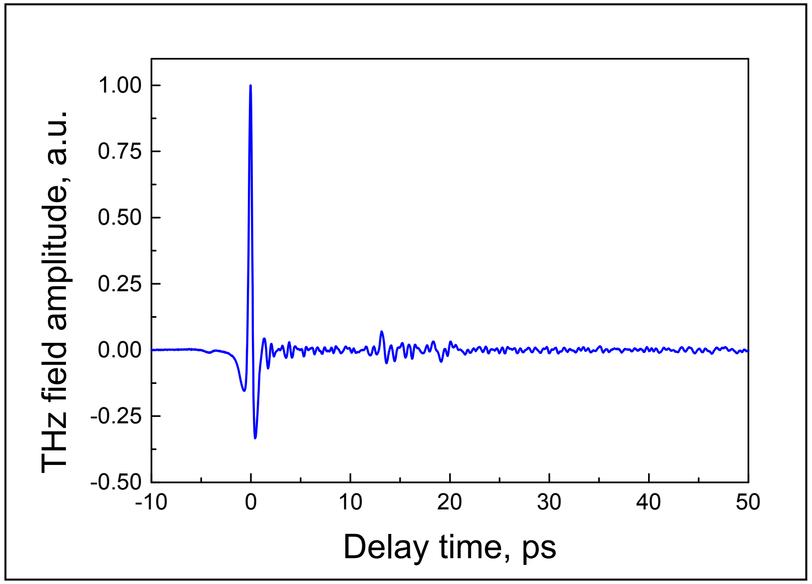
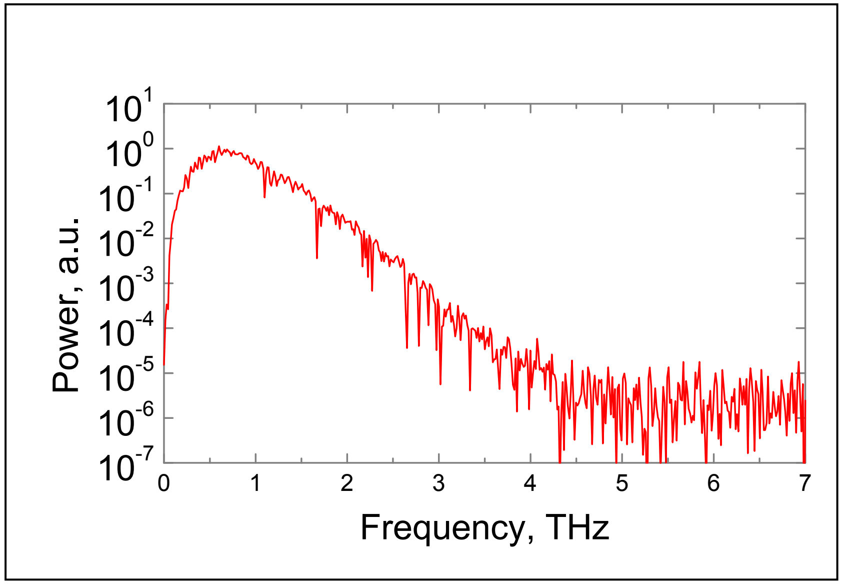
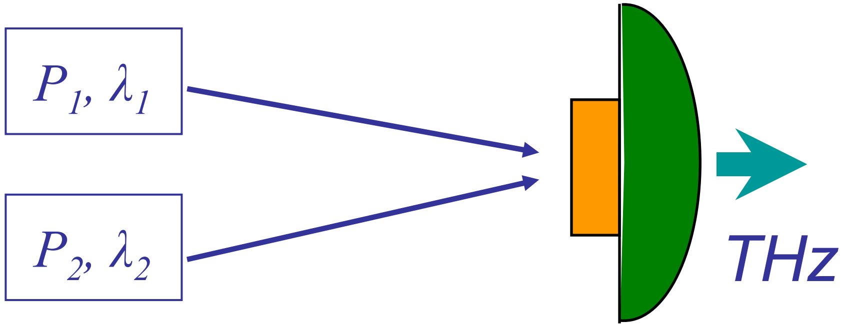
Terahertz pulses





- *Ultrafast electrical transients generated using femtosecond laser pulses;*
- *Their Fast-Fourier transform spectrum is shown on the right;*
- *Signal-to-noise ratios better than 60 dB easily achievable;*
- *Coherent detection – both amplitude and phase of different frequency components can be measured.*

THz optical mixers



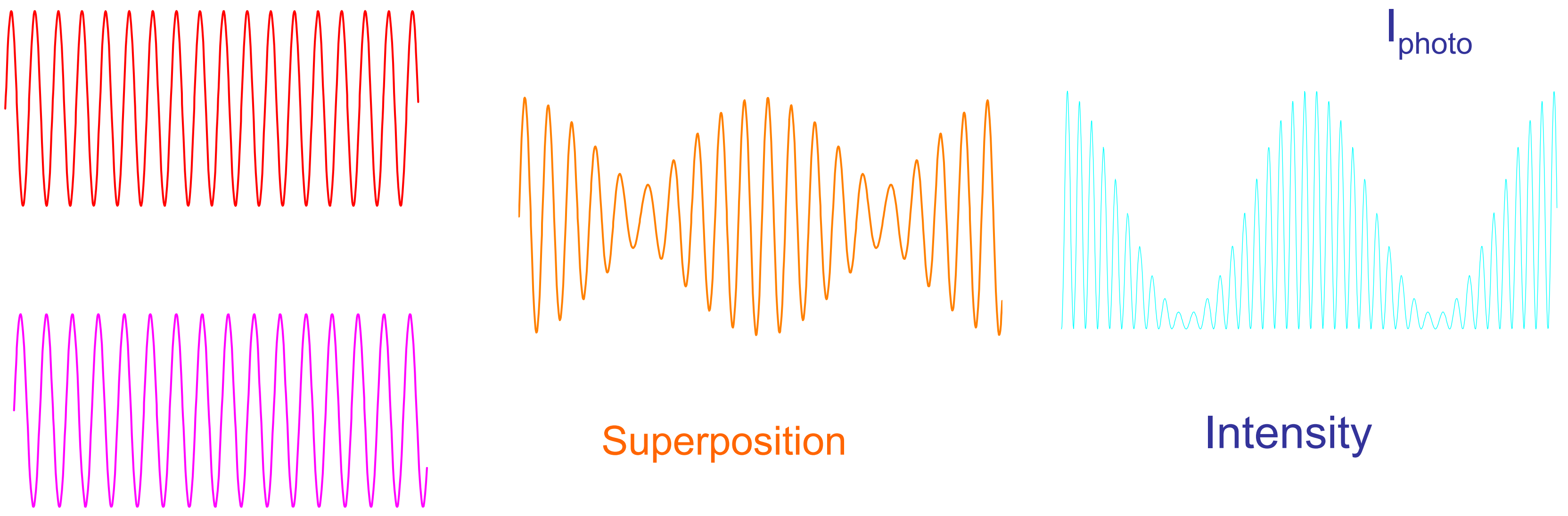
P_1, λ_1

P_2, λ_2

THz

tunable GaAs lasers
$\lambda_1 \neq \lambda_2 \cong$ 780 nm (380 THz)

photomixer
on Si lens



I_{photo}

Superposition

Intensity

Important material parameters

Energy bandgap – semiconductor should be photosensitive at the laser wavelength.

- **THz pulse emitters**: dark resistance, electron mobility, breakdown field, lifetime (shorter that the laser pulse repetition period).
- **THz pulse detectors**: electron trapping time, electron mobility, dark resistance.
- **Optical mixers**: electron and hole trapping times, dark resistance.

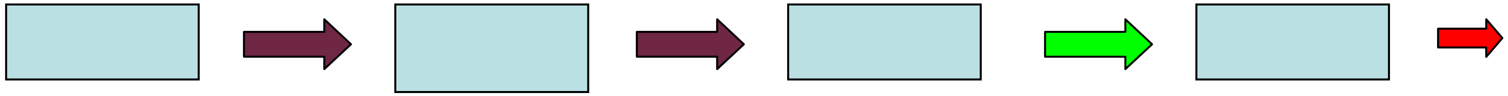
TDS with Ti:sapphire laser

Advantages:

* *Mature laser technology (700-800 nm);*
* *LTG GaAs – material sub-ps lifetimes, high resistivity, electron mobility, and with energy bandgap matching the laser photon energy.*

Disadvantages:

* *Complex optical pumping scheme;*
* *Cannot be made much smaller and cheaper.*



Diode laser bar
λ=808 nm

Nd:YAG laser
λ=1064 nm

2 harmonics
λ=532 nm

Ti:sapphire
λ=800 nm

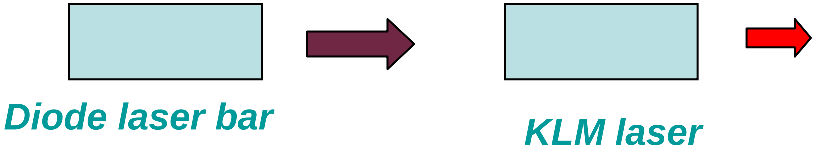
Infrared fs lasers

Advantages:

- ***1 μm or 1.55 μm wavelength range solid-state or fiber laser are already commercially available;***
- ***Directly pumped by diode laser bars;***
- ***Compact, efficient, cheaper.***

Disadvantages:

- ***Semiconductor material similar to LTG GaAs but sensitive to longer wavelengths required;***
- ***Longer wavelength means narrower energy bandgap and smaller dark resistivities.***



Diode laser bar

KLM laser

Choise of materials

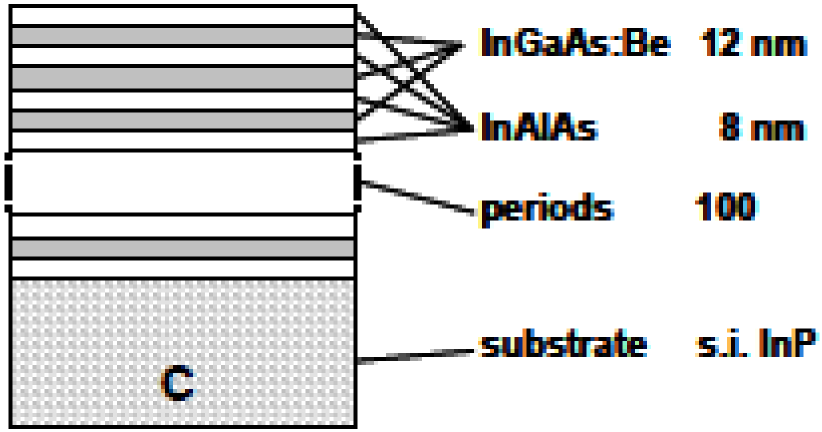
$In_xGa_{1-x}As$:

- LTG (at 200°C) on GaAs. x=0.25 (λ~1.05 μm); dark resistivity $8 \cdot 10^3$ $\Omega \cdot$cm, lifetime ~7 ps.
- LTG (at 180°C) on InP substrates. x=0.53 (λ~1.5 μm): free electron density >10^{18} cm^{-3}, lifetime ~2 ps;
- LTG, Be-doped. x=0.53 (λ~1.5 μm): free electron density $5 \cdot 10^{16}$ cm^{-3}, lifetime ~2 ps;
- heavy ion implanted (Au^+, Br^+, or Fe^+): dark resistivity < 10 $\Omega \cdot$cm, electron lifetimes 0.5÷2 ps.

$GaSb_xAs_{1-x}$:

- LTG (at 170°C) on GaAs substrates. x=0.4 (λ~1.4 μm): dark resistivity ~ 10^4 $\Omega \cdot$cm.

Layered structures

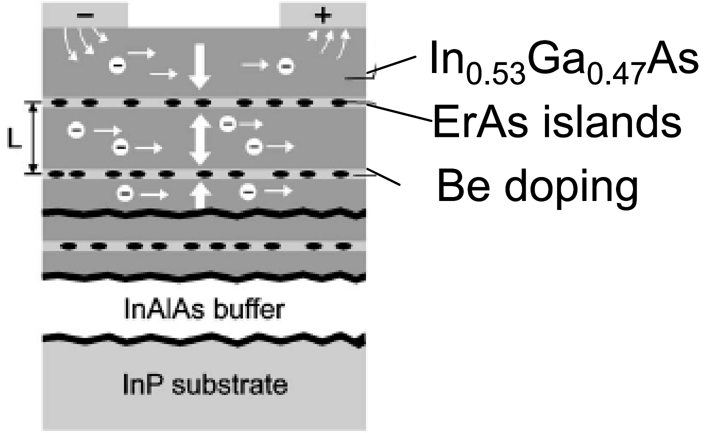


InGaAs – photoconductive layer;

Be- doping – for compensation of the residual donors;

InAlAs – LTG electron trapping layer.

B. Sartorius, Opt.Expr., **16**, 9565 (2008*)*



InGaAs – photoconductive layer;

Be- doping – for compensation of the residual donors;

ErAs –electron trapping nanoclusters.

F. Ospald, APL., **92**, 131117 (2008)

Our way to GaBiAs

- 1995 – 2003. Low-temperature MBE grown GaAs; heavy ion implanted GaAs for ultrafast optoelectronic applications;

- Search of a short-lifetime material with a low mismatch to GaAs.

- 2003. Papers from T. Tiedje and Kyoto groups on $GaBi_xAs_{1-x}$ grown by MBE. x=3.1% (S.Tixier et.al, APL) and x=4.5% (M. Yoshimoto et.al., Jpn.J. Appl. Phys.). Growth temperatures were 380°C and 350°C, respectively.

- 2005. Starting MBE growth at even lower substrate temperatures 240-330°C.

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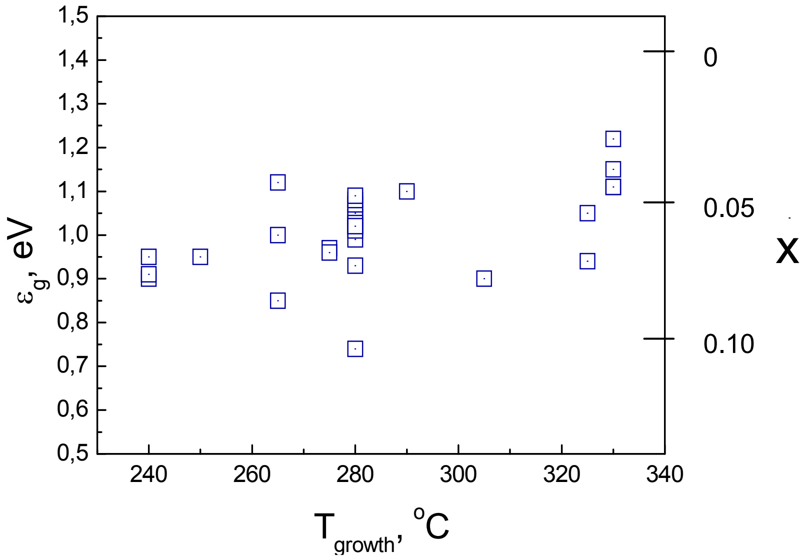
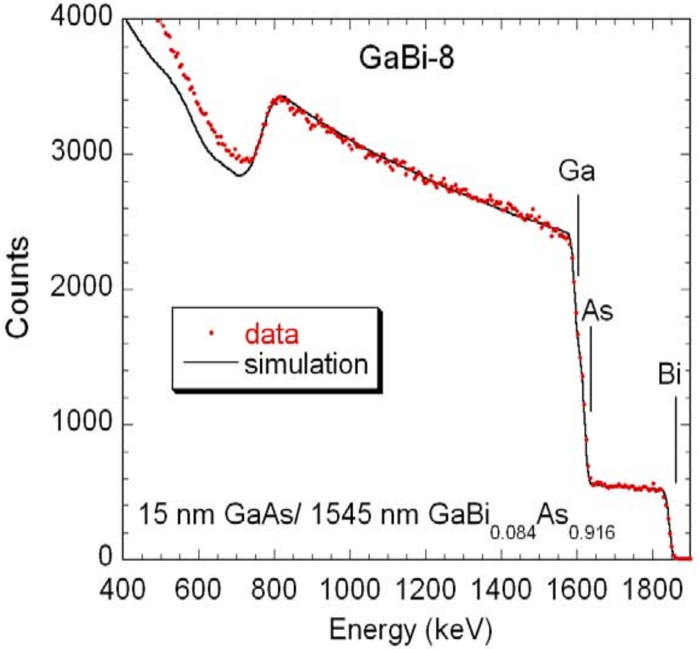
Growth technology

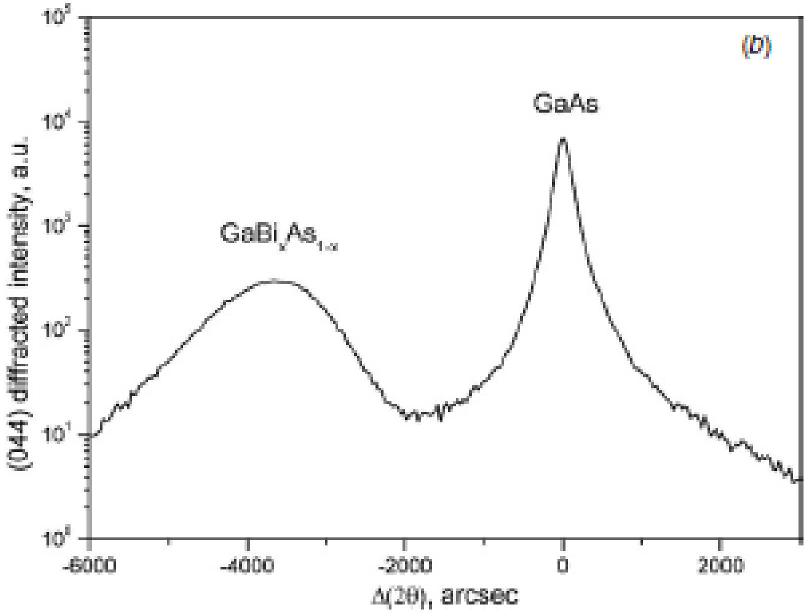


Bandgap versus the growth temperature for 30 GaBiAs growth runs.

- *Soviet –made MBE machine (ШТАТ).*
- *As$_4$ source.*
- *x=5 % (*K. Bertulis et.al. APL,2006*).*
- *x=8.5% (*V. Pacebutas et.al., Sem.Sc.Technol., 2007*).*
- *x=11 % (*V. Pacebutas et.al., J. Mater,Sc.., 2008*)*

Alloy composition



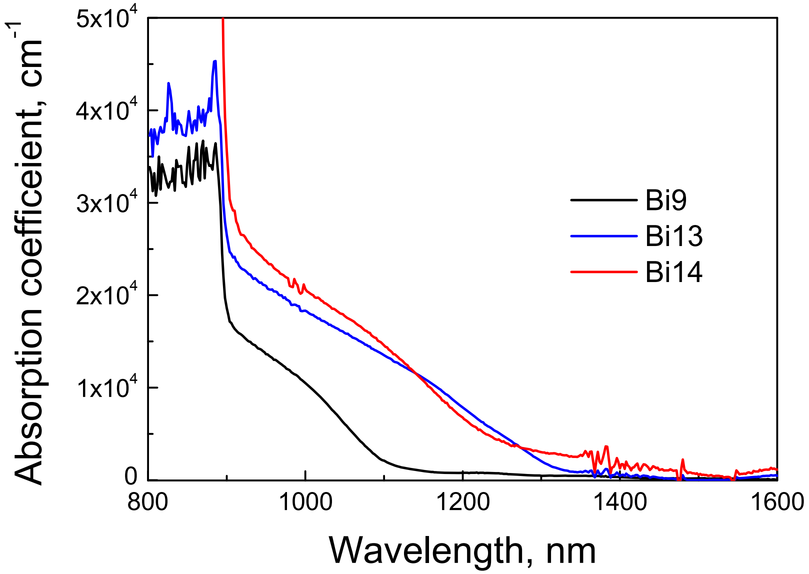


Rutherford Back-Scattering.

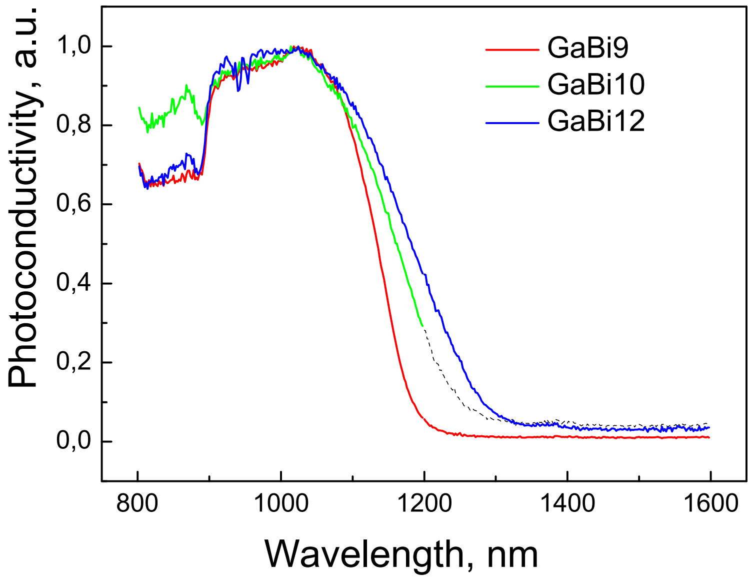
W. Walukiewicz, Lawrence Livermore Nat. Lab.

X-ray diffraction.

Energy bandgap

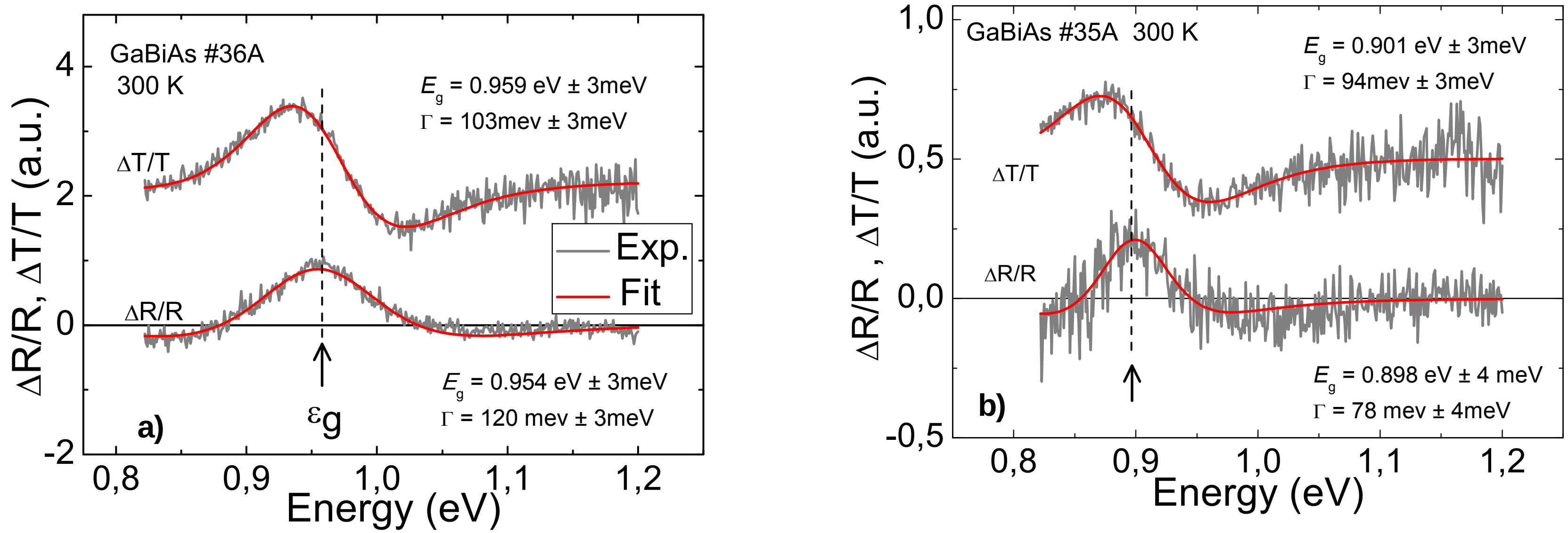


Optical absorption spectra at room temperature.



Photoconductivity spectra at room temperature.

Modulation spectroscopy



Photomodulated transmittance (ΔT/T) and photomodulated reflectance (ΔR/R) spectra for two GaBiAs samples measured at room temperature.

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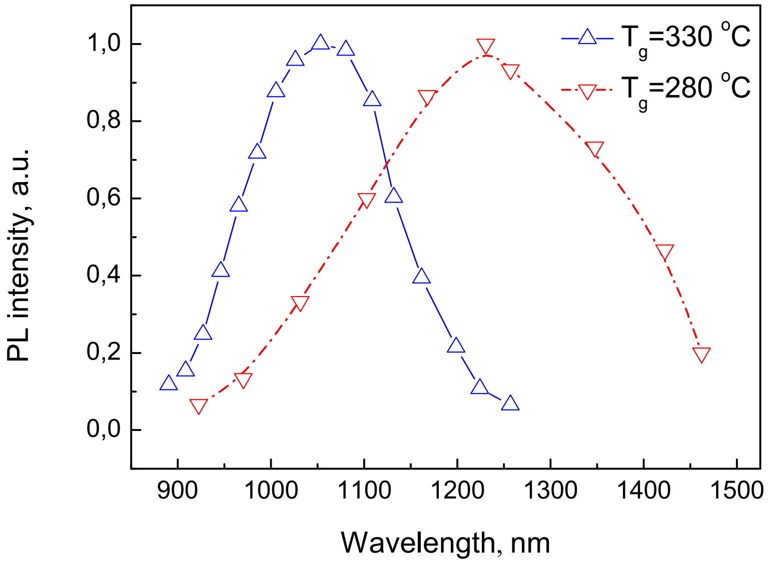
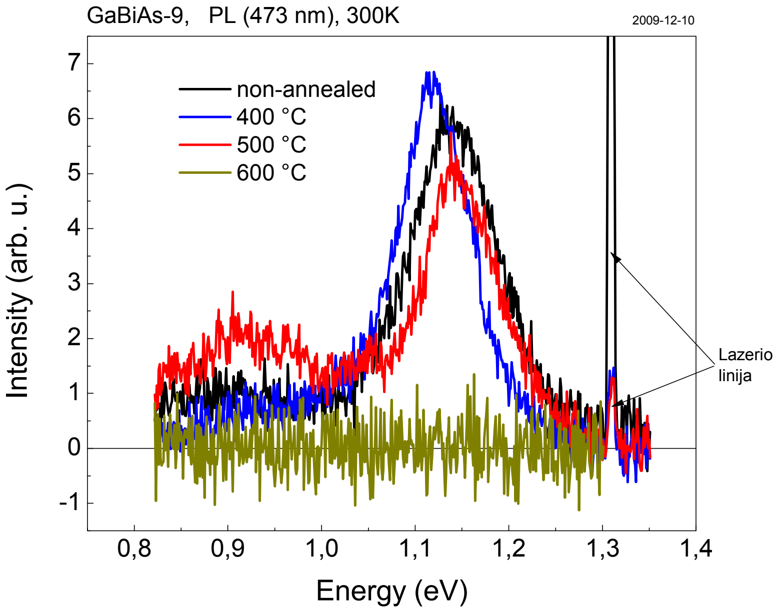
Photoluminescence





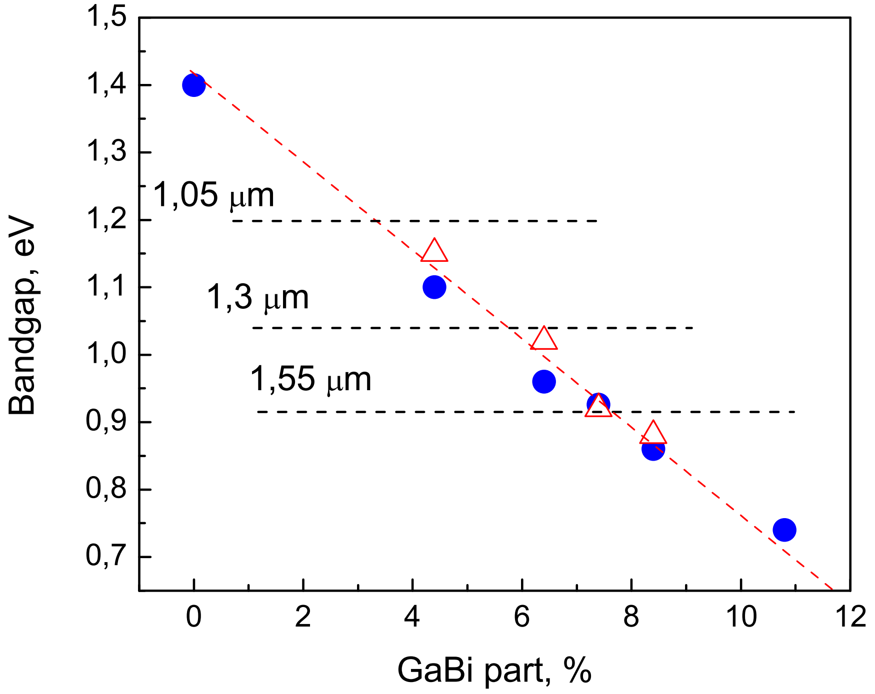
GaBiAs layers with the carrier lifetime shorter than 10 ps. PL measured by frequency up-conversion, single-photon counting technique.

Prof. S. Marcinkevičius lab., KTH, Stockholm.

GaBiAs layer with a long carrier lifetime (~200 ps non-annealed). PL measured by a standard cw technique.

Complex annealing behavior.

Energy bandgap of GaBiAs



V. Pacebutas et.al., Sem.Sc.Technol., 2007

With the addition of Bi, the energy bandgap decreases at a rate of -62 meV/%Bi.

***Other material parameters**:*

Conductivity – p-type.

Hole concentration ~10^{15}cm^{-3},

Hole mobility 20-200 cm^2/Vs (decreasing in layers with a larger GaBi part).

Resistivity – typically 100's of Ω·cm for nominally undoped layers; >10^4 Ω·cm in Si-compensated GaBiAs.

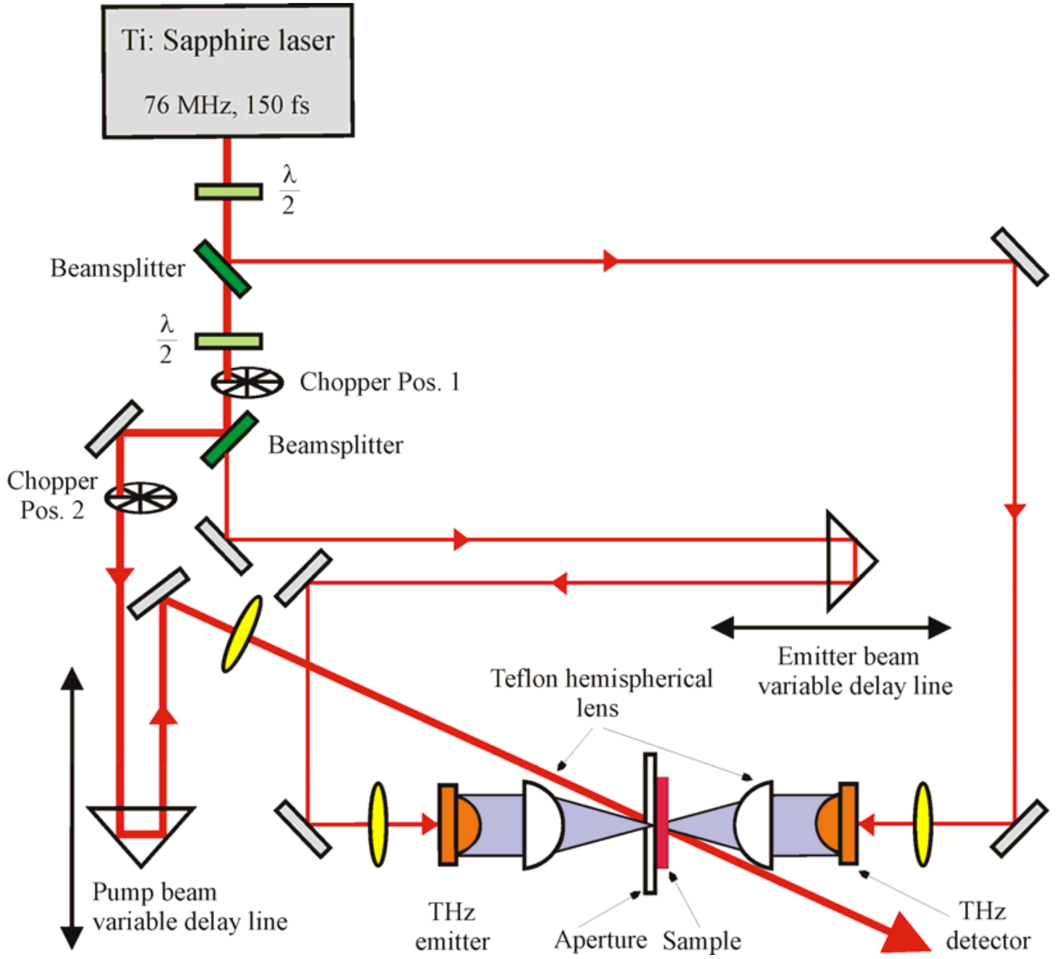
Lifetime measurement

Optical pump – THz probe experiment. THz pulse absorption caused by non-equilibrium electrons is measured at different time delays with respect to the sample photoexcitation.

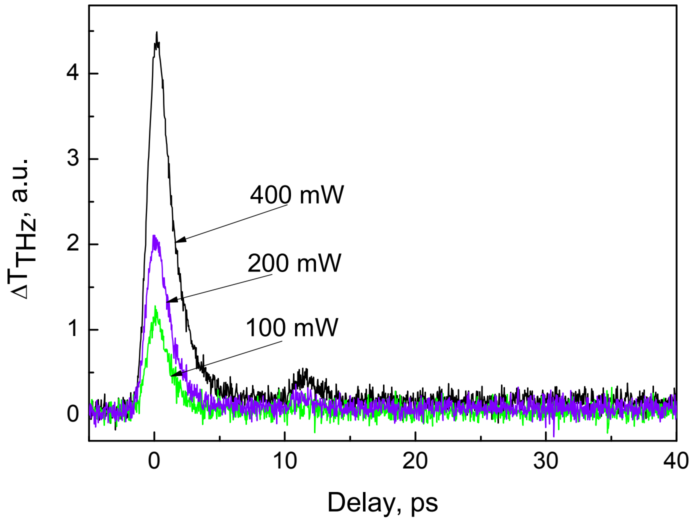
Optically induced change in THz pulse transmittance is proportional to

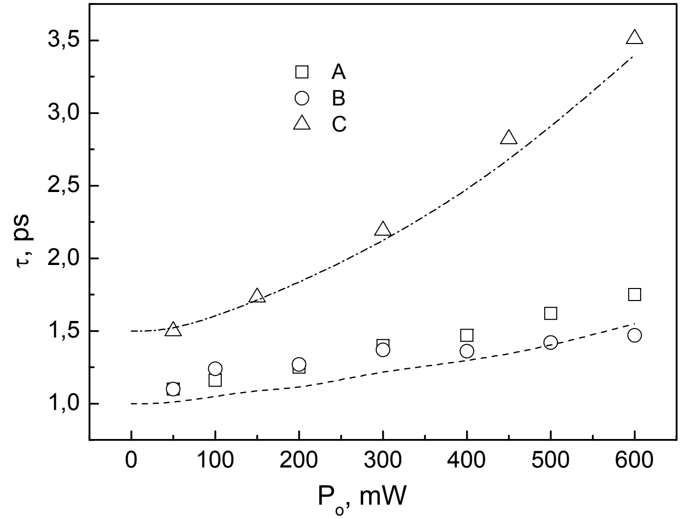
$\ln(I/I_0)=-\alpha_i L=-(4\pi n_i/I_0)L\sim\sigma_{dc}\sim N\mu$

Both the electron mobility and their lifetime can be determined.



Electron lifetime in GaBiAs





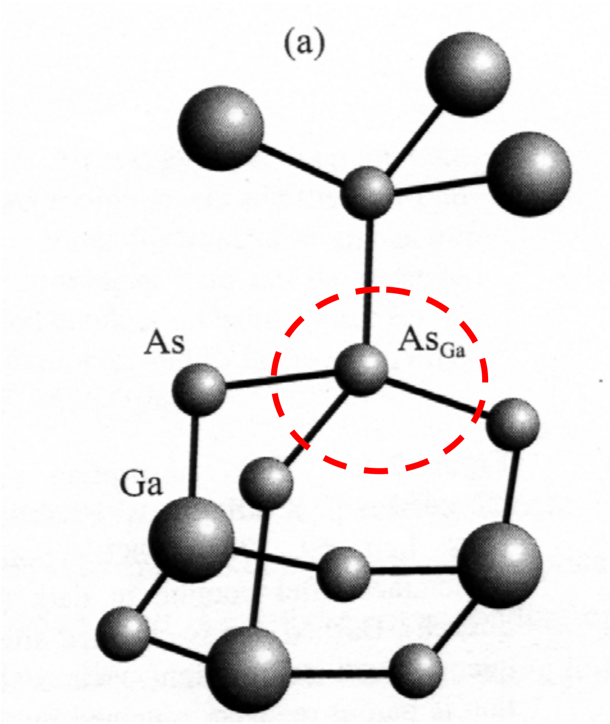
Lifetime varies from less than 1 ps to more than 200 ps. Electron mobility as determined from the amplitude of the induced THz absorption >2000 cm^2/Vs.

Electron lifetime is dependent on the photoexcitation level. Trap filling effect.

Best fit with a single trap model obtained for the capture cross-section of 4.5$\cdot 10^{-13}$ cm^2 and the trap density of 3$\cdot 10^{16}$ cm^{-3} (sample A) and 4$\cdot 10^{16}$ cm^{-3} (samples B and C).

V. Pačebutas et.al., pss(c), (2009)

Arsenic antisites



The main carrier trapping center in LTG GaAs.

Electron capture cross-section by As_{Ga} in GaAs– 10^{-13} cm^2

A. Krotkus et.al. IEE Proc. Optoelectron.,

In LTG GaAs the lifetime increases after annealing because the majority of the excess As atoms precipitate into nm size clusters.

As-antisite. Point defect leading to a deep level in the band gap.

M.Kaminska, E.Weber, (1990)

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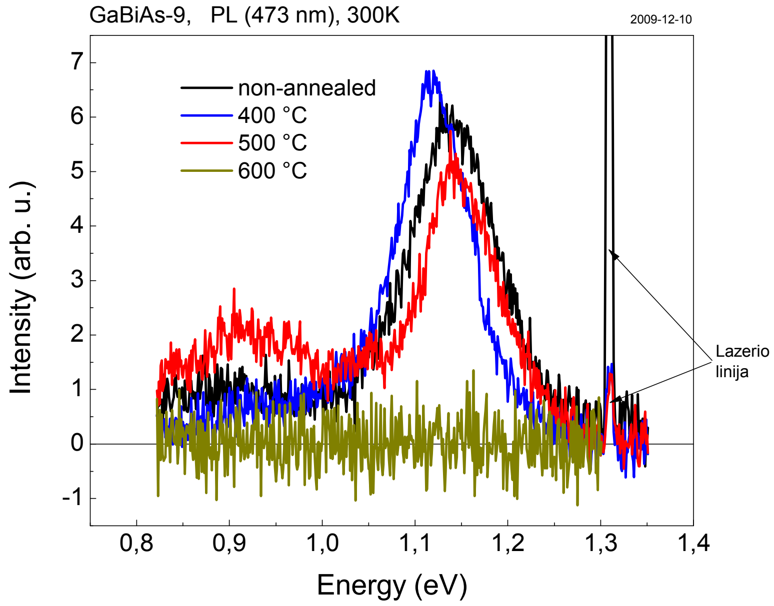
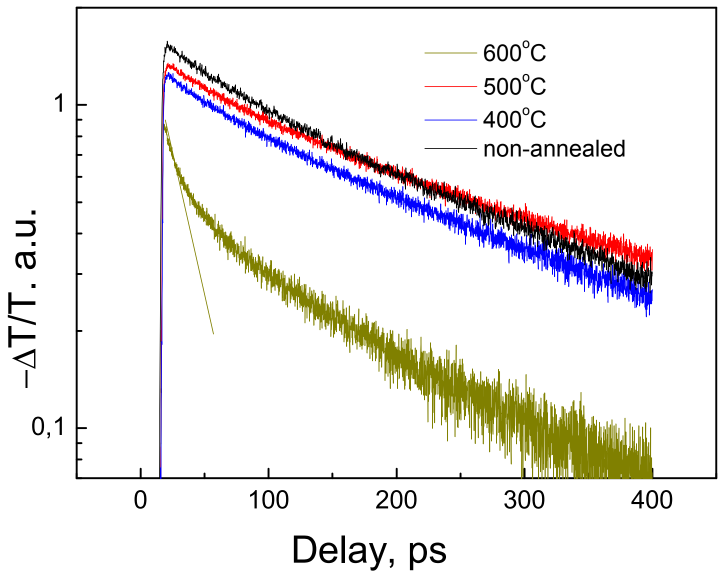
Effect of the annealing





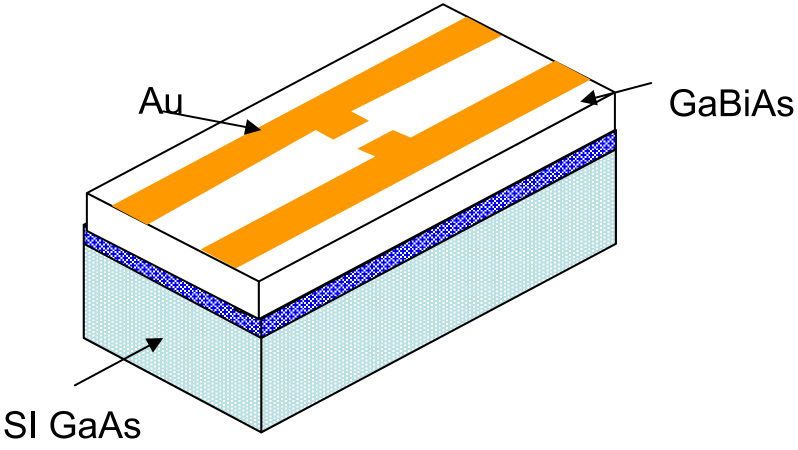
Photoluminescence in GaBiAs layer with a long carrier lifetime (~200 ps non-annealed). PL measured by a standard cw technique.

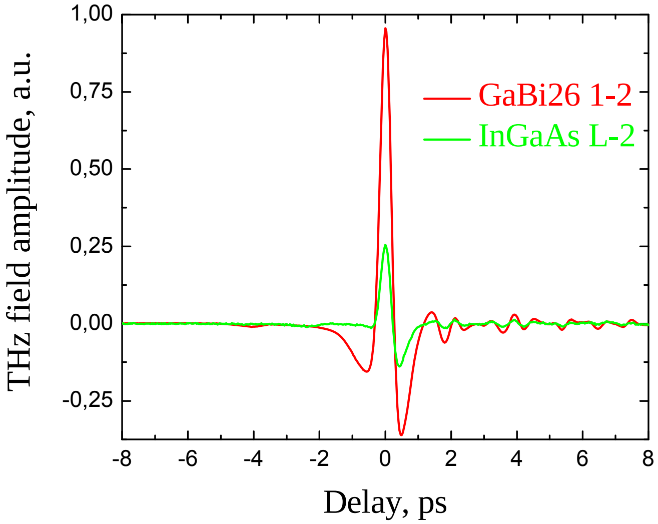
Complex annealing behavior. Additional PL band at ~1.3 μm (Bi-clusters?)

THz probe measurement.

Lifetime in as-grown layer is ~200 ps, it slightly increases after anneal at 400 and 500°C, and drops to <30 ps at T=600°C.

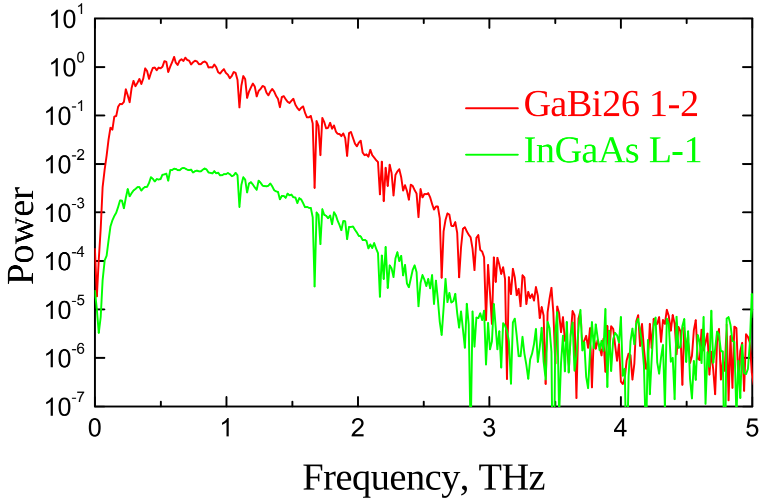
THz detectors



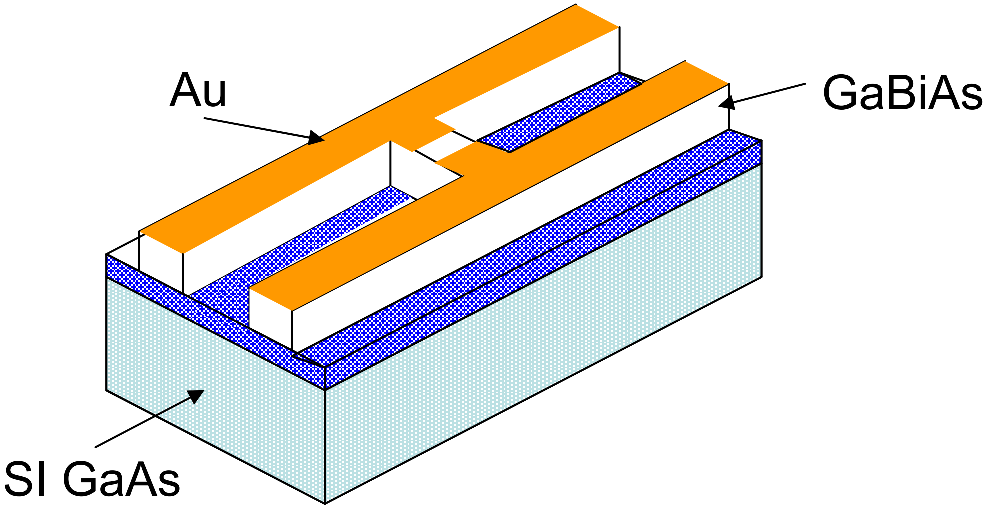


The width of the gap – 15 μm.
Detected THz pulse amplitude is 5 times and S/N ratio 100 times larger than when detector made from LTG InGaAs layer is used.
THz emitter is p-type InAs.

G. Molis et.al., Electron. Lett. 43,190-191 (2007)



THz emitters



The geometry of the antenna is similar to one used for THz detectors, except for mesa-etching of GaBiAs layer area between the microstriplines.

GaBiAs doping with Si used for residual p-type conduction compensation.

Dark resistance of the emitter >100 MΩ. Breakdown field larger than 50 kV/cm.

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Efficiency measurement

*A **Golay Cell** is a type of detector mainly used for FIR spectroscopy. It consists of a small metal cylinder which is closed by a blackened metal plate at one end and by a flexible metalized diaphragm at the other. The cylinder is filled with Xe and then sealed.*

Measurements of THz power as functions of the bias voltage and the optical power.

Optical-to-THz conversion efficiency obtained was up to $7 \cdot 10^{-4}$, much better than $\sim 10^{-5}$ reached with other similar systems.

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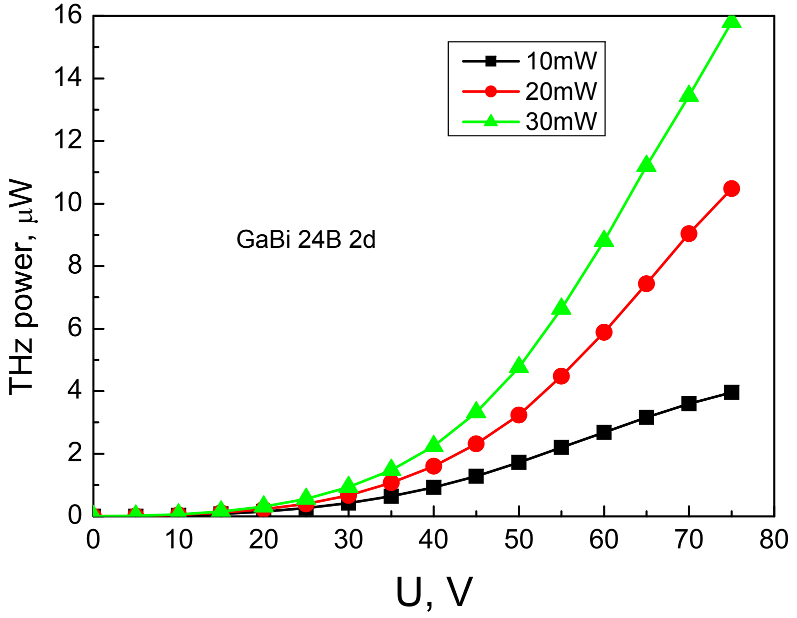
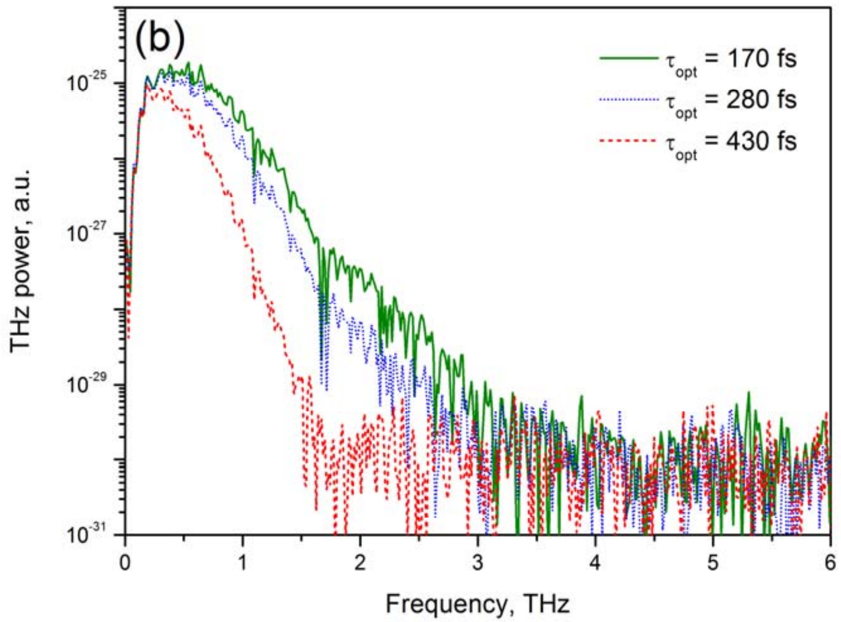
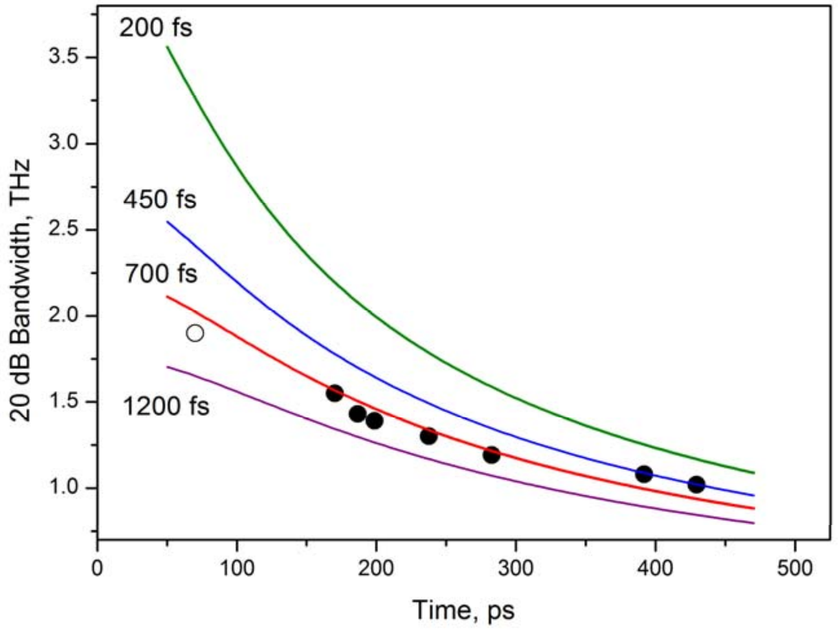


THz-TDS with a fiber laser

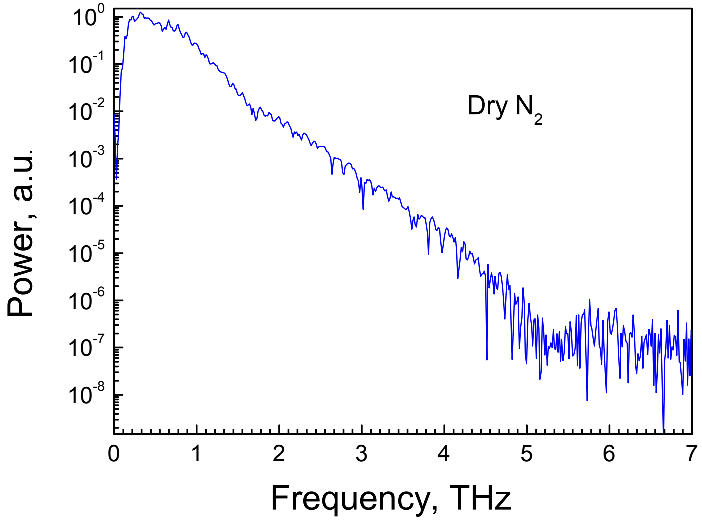


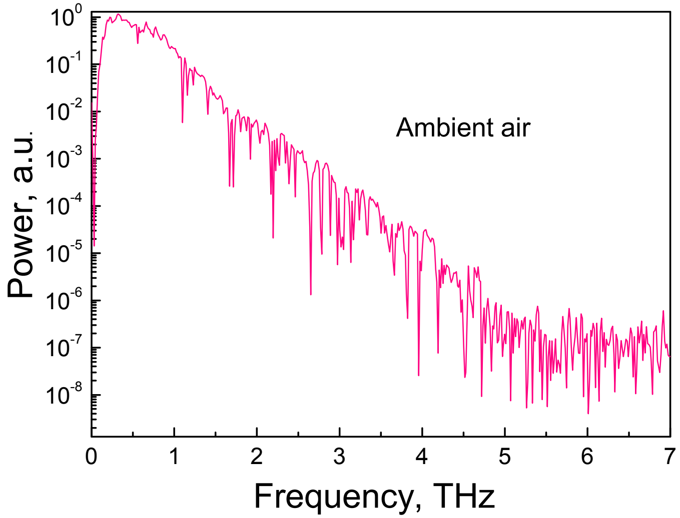


The Yb:fiber oscillator operated at a repetition rate of 45 MHz; an average output power of ~8 mW and ~11 mW was used for photoexcitation of the THz emitter and detector respectively.

20 dB-bandwidth of THz-TDS system as a function of the optical pulse duration. Solid lines – calculations for different carrier lifetimes in the detector.

THz spectra



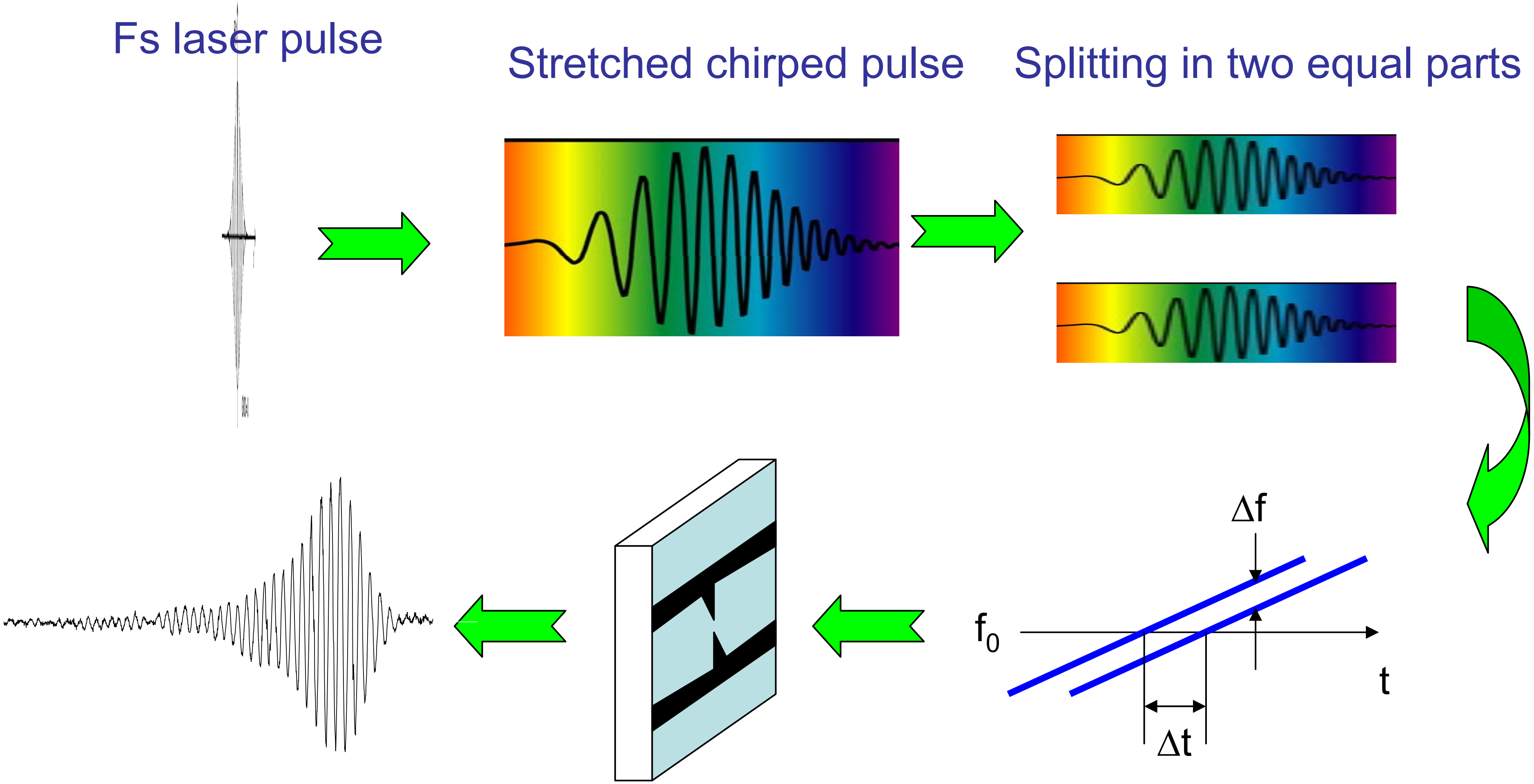


Yb:KGW laser, 1030 nm, 70 fs.

Spectral width ~5 THz, S/N ratio ~70 dB.

Average fs laser power of ~ 10 mW is sufficient for activating both the emitter and the detector.

THz burst generation



Fs laser pulse

Stretched chirped pulse

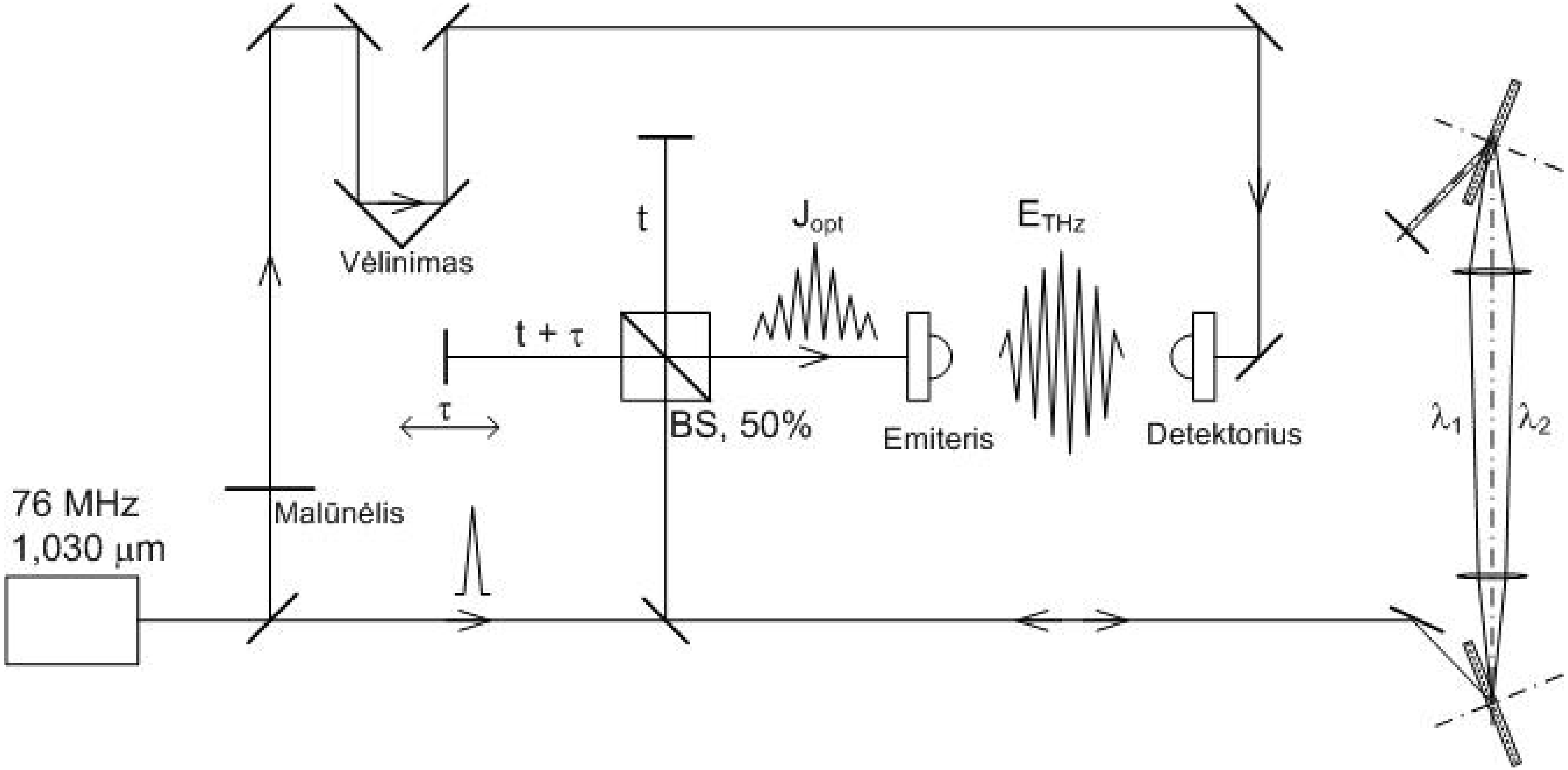
Splitting in two equal parts

Variable delay between two parts

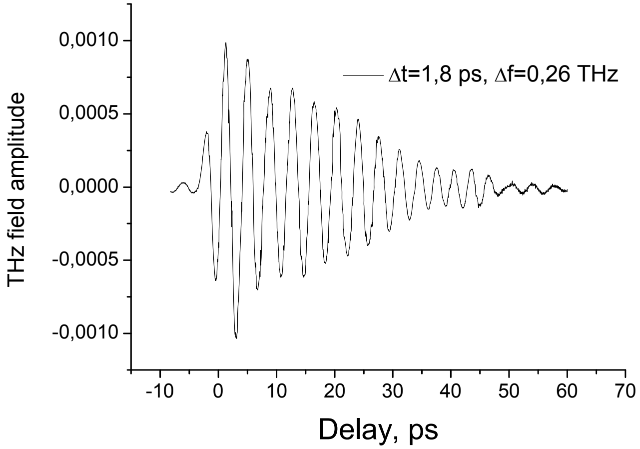
Photoconductive antenna

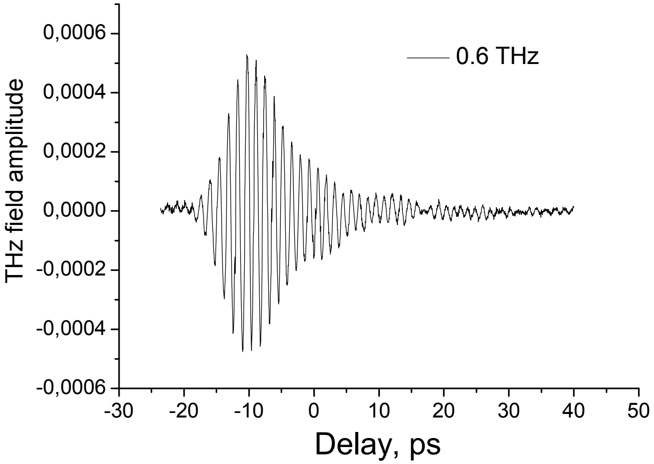
THz radiation

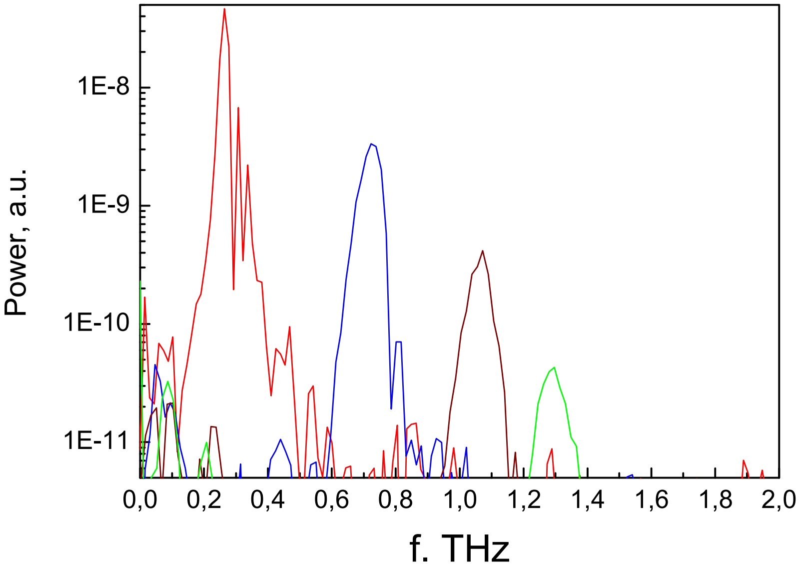
Experimental set-up



THz bursts from GaBiAs emitter





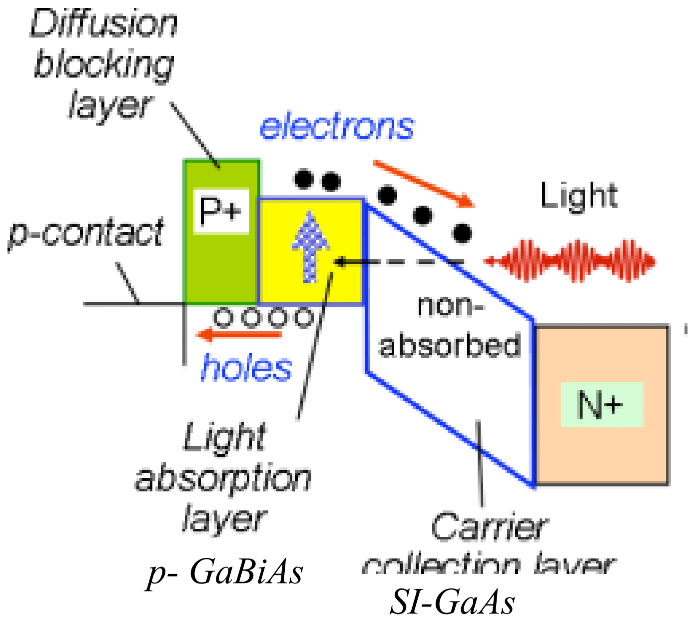


Emitter – Hertzian dipole, length 70μm, resonance ~0.5 THz.

Yb:KGW laser pulses stretched to 30 ps, average optical power in both arms – 25 mW, bias voltage 30 V.

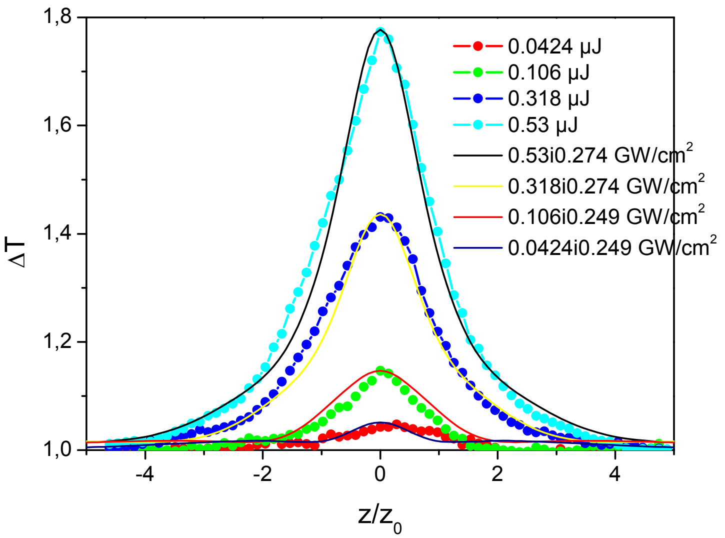
Maximum frequency observed 1.3 THz.

Other ultrafast applications



Uni-travelling carrier photodiode.

Response time limited by the electron sweep-out through the collection layer. Bandwidths >1THz demonstrated.



Open aperture Z-scan measurement. Large optical bleaching effect with relatively low saturation intensity.

Possible applications in saturable absorbers for mode-locked lasers and all-optical switches.

Conclusions

- Dilute GaBiAs due to its large electron mobility in a material with sub-picosecond carrier lifetimes is a prospective material for ultrafast optoelectronic application in the wavelength range of from 1 μm to 1.5 μm.

- THz time-domain-spectroscopy system with components manufactured from GaBiAs and activated by femtosecond pulses of compact 1-mm wavelength laser was demonstrated.

- This material shows great prospects in other ultrafast device applications, such as cw THz optical mixers, semiconducting saturable absorbers, and all-optical switches.