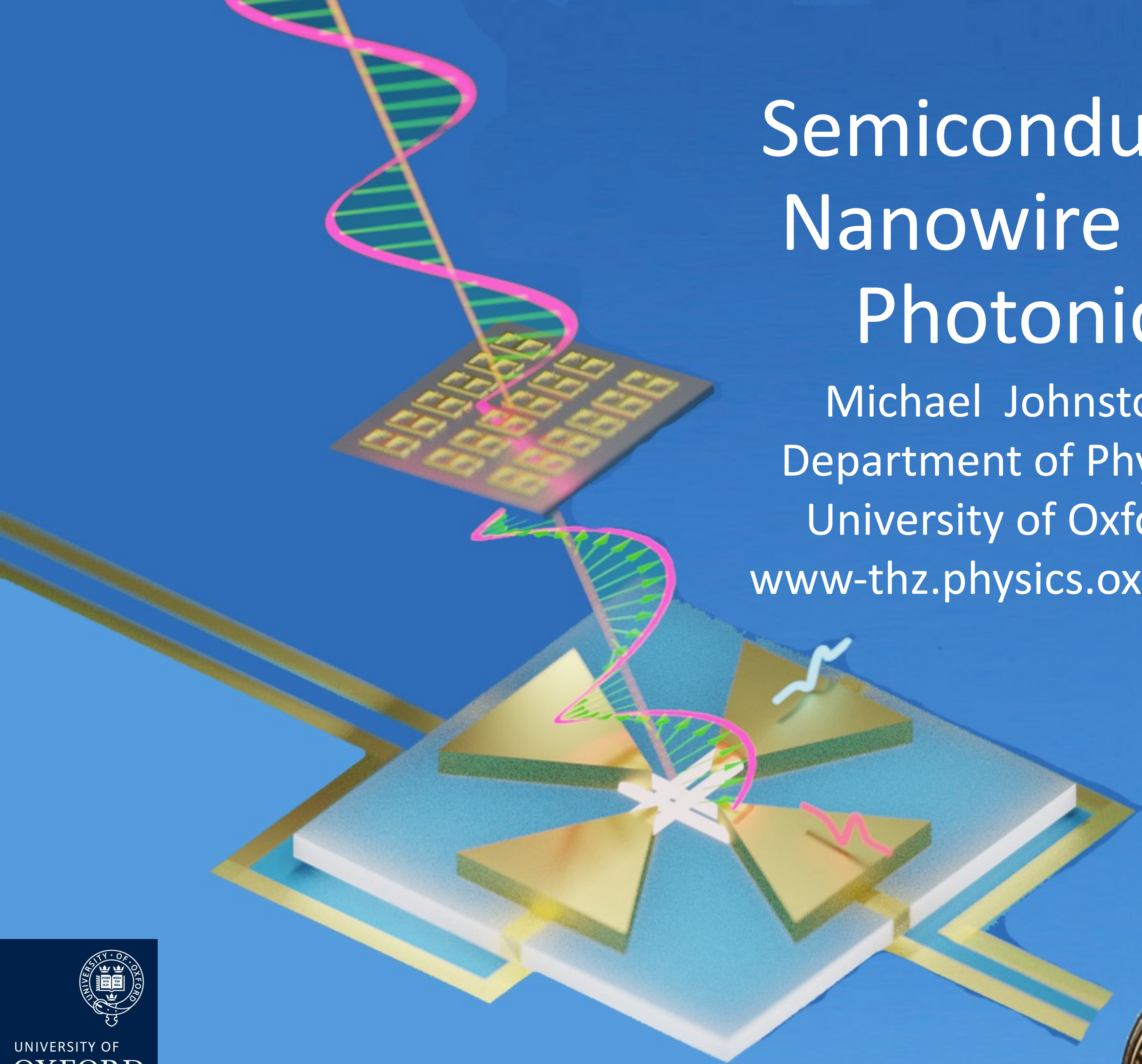
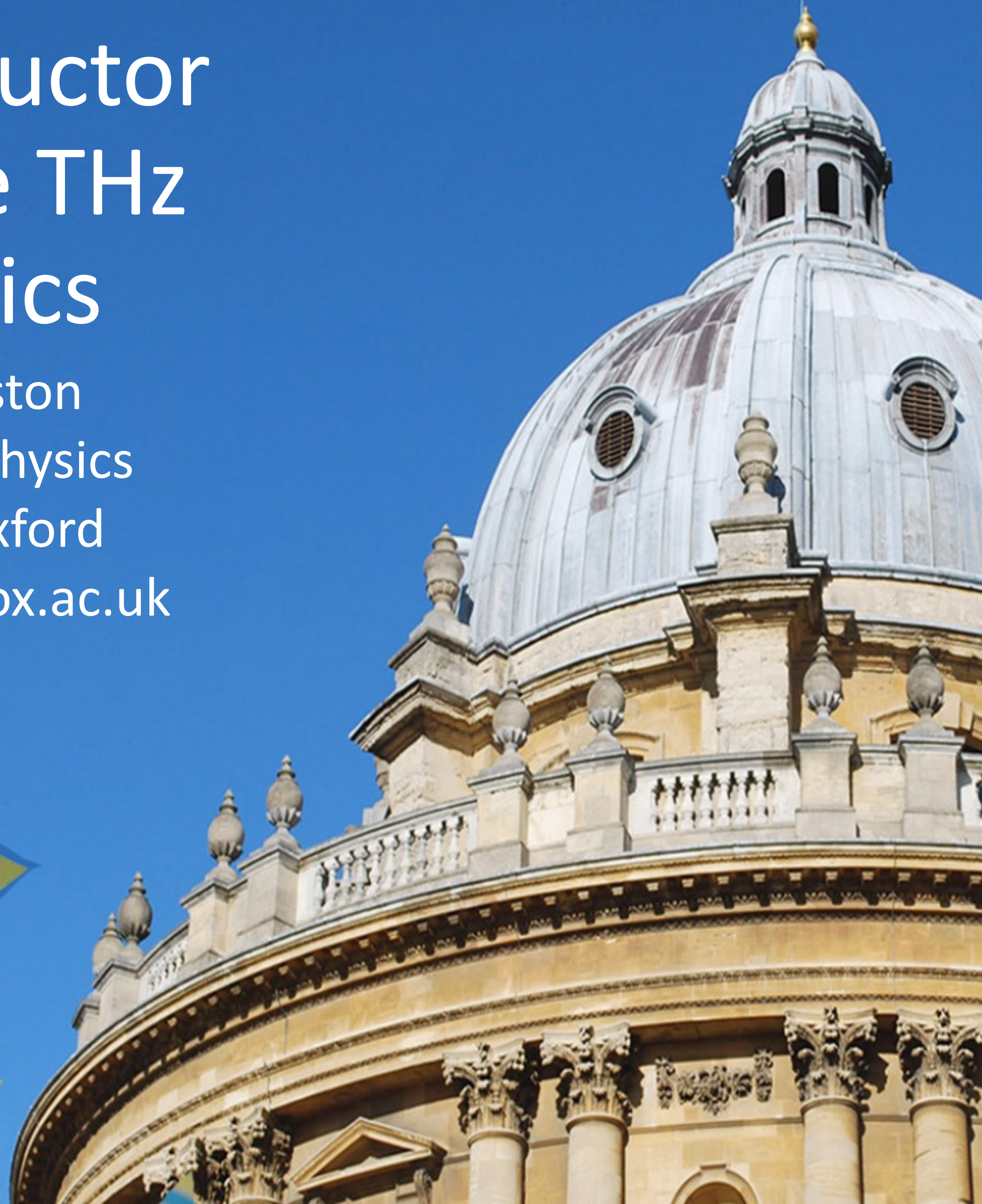


Semiconductor Nanowire THz Photonics

Michael Johnston
Department of Physics
University of Oxford
www-thz.physics.ox.ac.uk



UNIVERSITY OF
OXFORD

Commad 1996, Canberra

Optical properties of δ-doped GaAs *nipi* super-lattices

M.B.Johnston[†] M.Gal[†] G.Li[*] C.Jagadish[*]

[†] *School of Physics*
University of New South Wales, Sydney, NSW 2052
[*] *Department of Electronic Materials Engineering*
The Research School of Physical Sciences and Engineering
The Australian National University, Canberra, ACT 0200

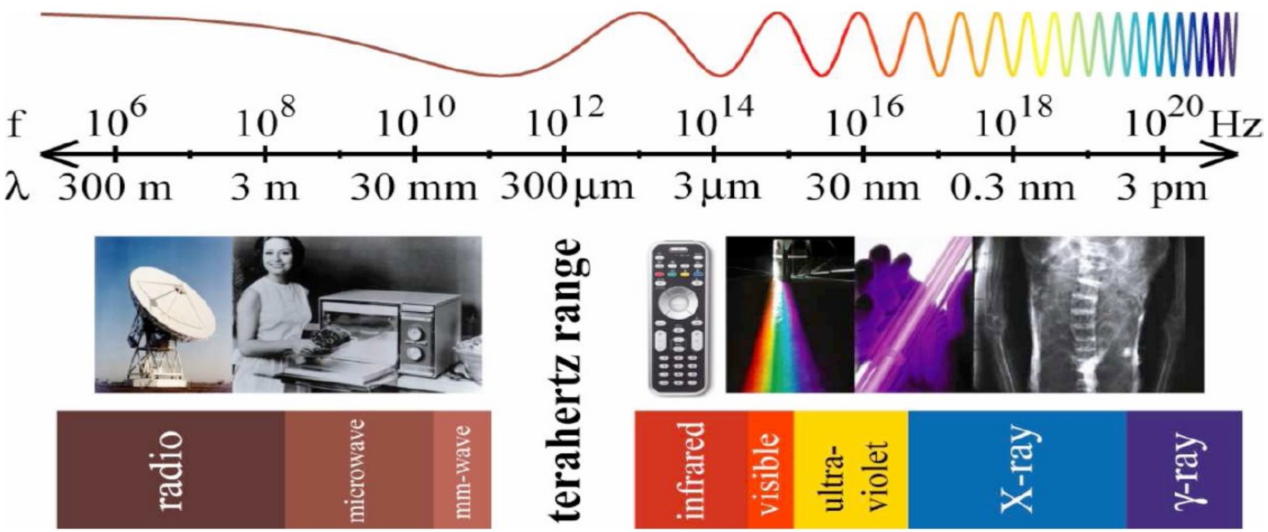
Abstract

A δ-doped GaAs *nipi* super-lattice has been examined using photoluminescence spectroscopy. Intensity dependent photoluminescence spectra were measured over 5 orders of magnitude (1 kW/cm^2–8 mW/cm^2). A significant shift in the photoluminescence emission maxima (155 meV) was evident over this range. Time resolved photoluminescence spectra were observable over 6 temporal orders of magnitude (10 ns–10 ms). The strong photoluminescence signal over such a long decay time allowed the relaxation of the *nipi* effective bandgap after optical excitation to be observed.

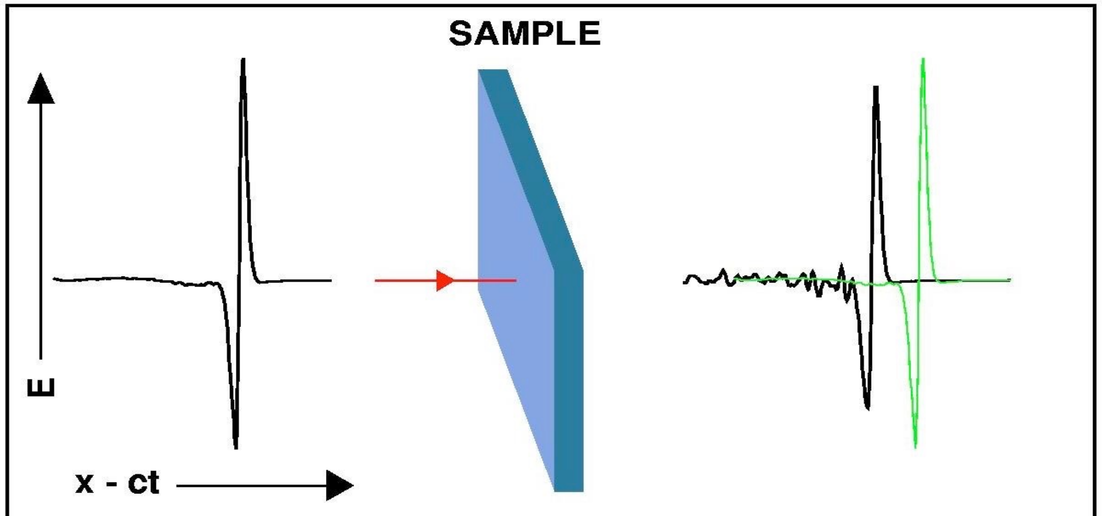
A Introduction

A doping superlattice is a semiconductor which has a periodic doping profile across its growth direction. Doping superlattices differ from compositional (or heterostructure) superlattices since only the concentration of doping impurities is modulated rather than

There are many applications of THz photonics

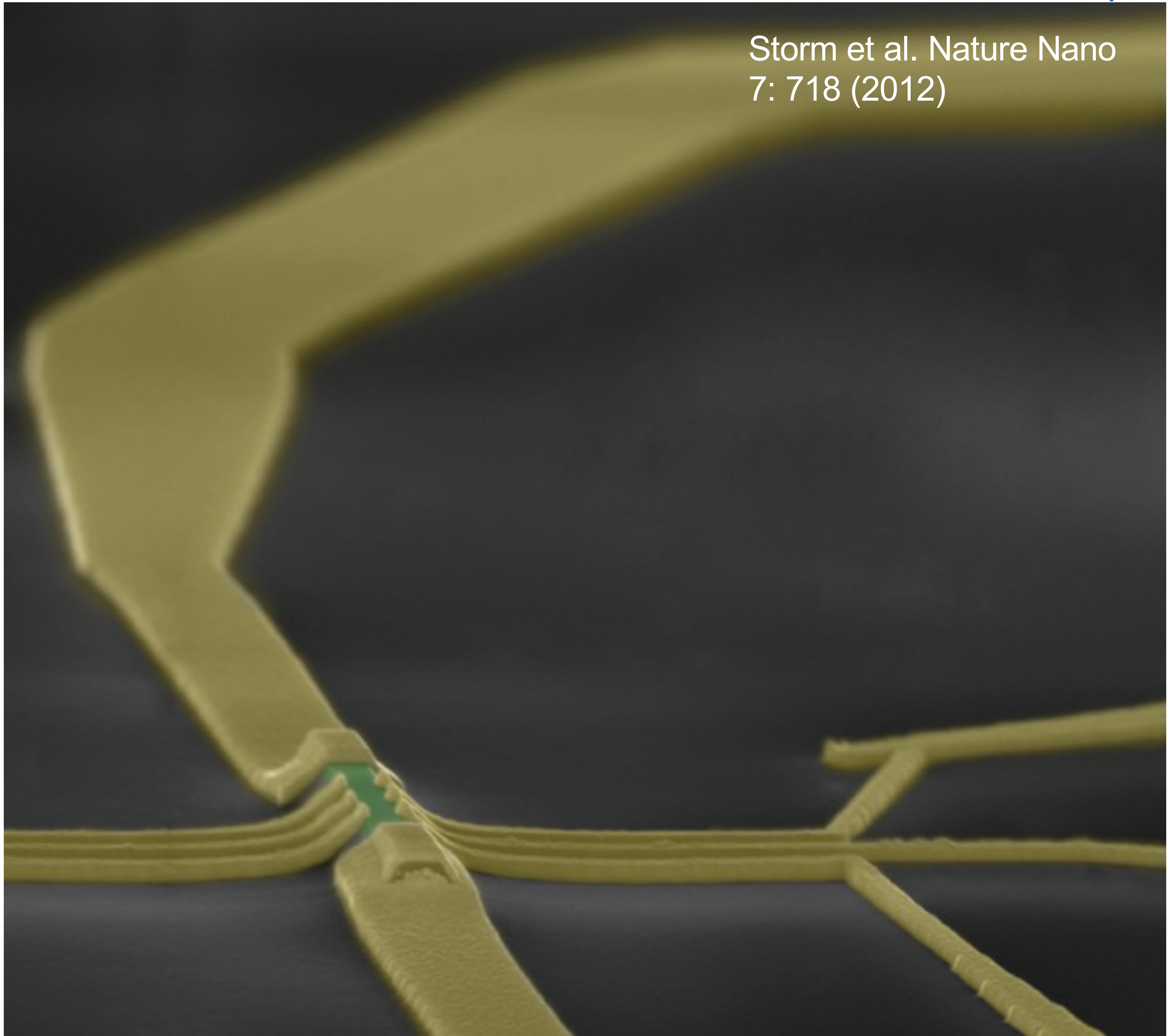


UNITS: 1THz = 300μm = 4.1meV = 47.6K



- **Communications :** 6G?
- **Plasma diagnostics**: electron density profiles and fluctuations, magnetic field strengths.
- **Condensed Matter Physics:** THz spectroscopy covers energy range of correlated systems (excitons, Cooper Pairs, phonons, plasmons…)
- **Chemistry:** Also energy range for molecular rotations and vibrations
- **Electrical Engineering:** Non-contact probe of conductivity, high resolution electric field detection in devices (chip diagnostics)
- **Non-destructive Testing:** Time resolved probe of dielectric properties of materials & devices
- **Medical Imaging:** Non ionising (medical/dental imaging)
- **Security screening**
- MANY MORE USES ACROSS DIVERSE FIELDS!! Review: THz Science and Technology Roadmap *J. Phys. D* **50** 043001, 2017

Standard versus Non Contact Probes of Electrical Conductivity

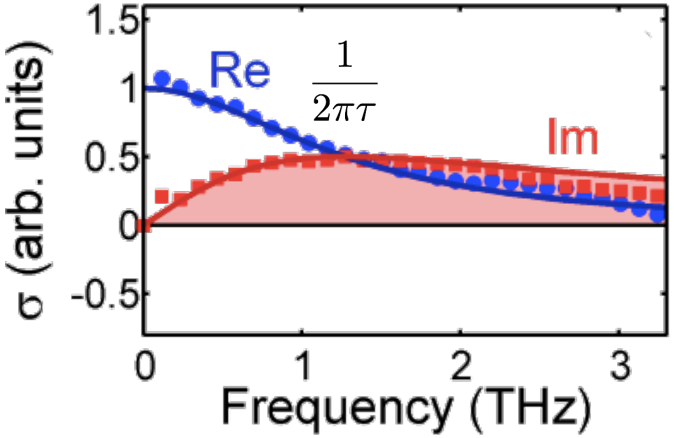


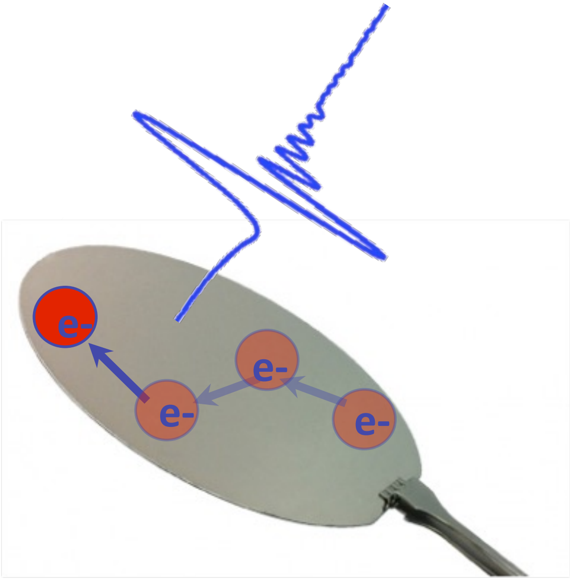
AC conductivity of GaAs: bulk vs nano

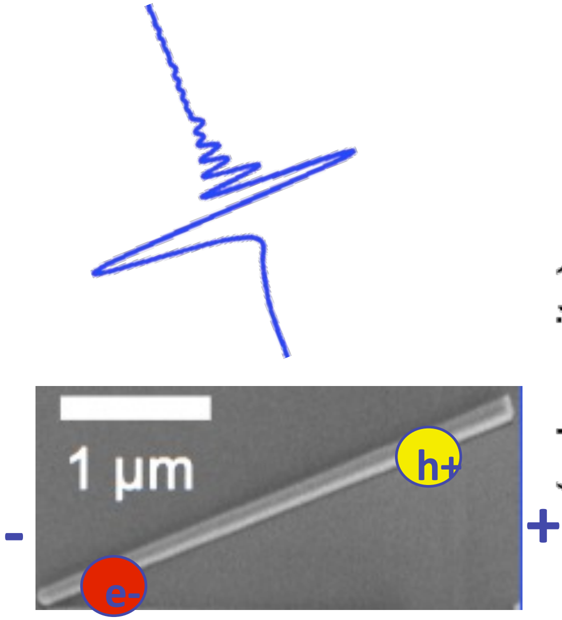
DC $\mathbf{J} = \sigma \mathbf{E}$ e.g. Drude Conductivity $\sigma_0 = \frac{ne^2\tau}{m_e}$

AC $\mathbf{J}(\omega) = \sigma(\omega)\mathbf{E}(\omega)$ $\sigma(\omega) = \sigma_0 \frac{1}{1 - i\omega\tau}$

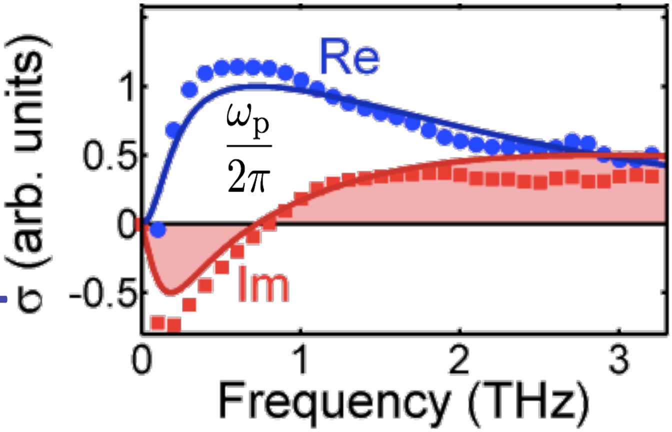
n-type GaAs wafer





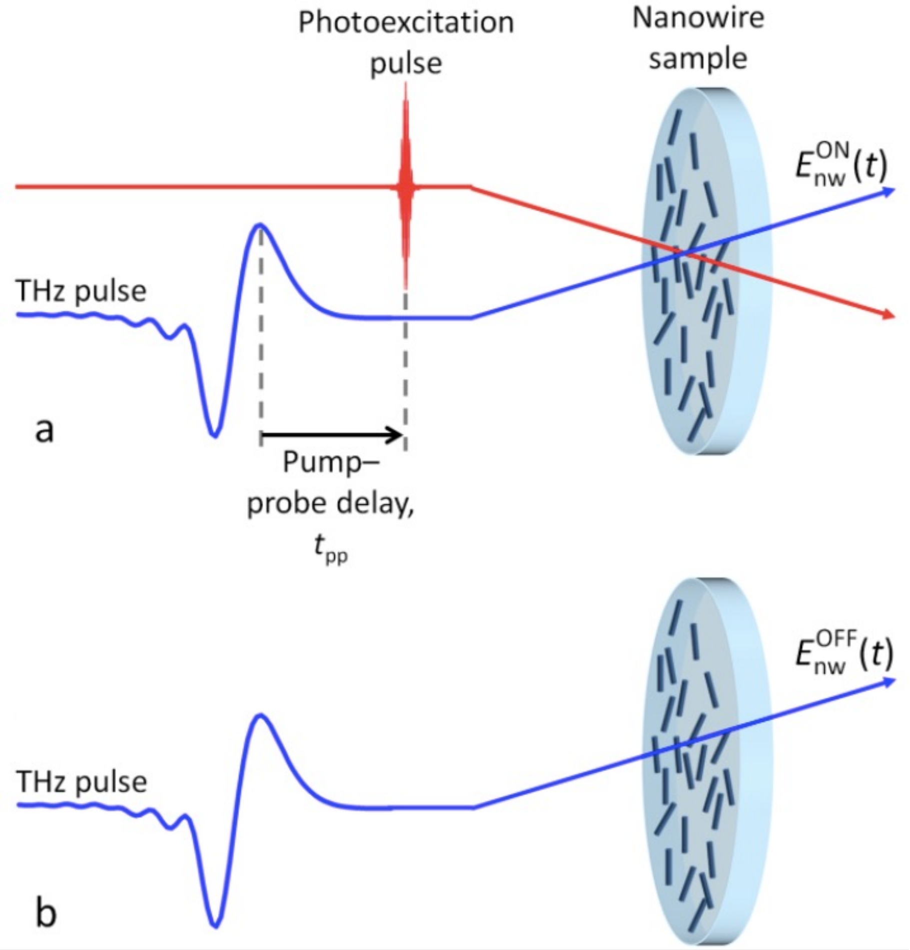


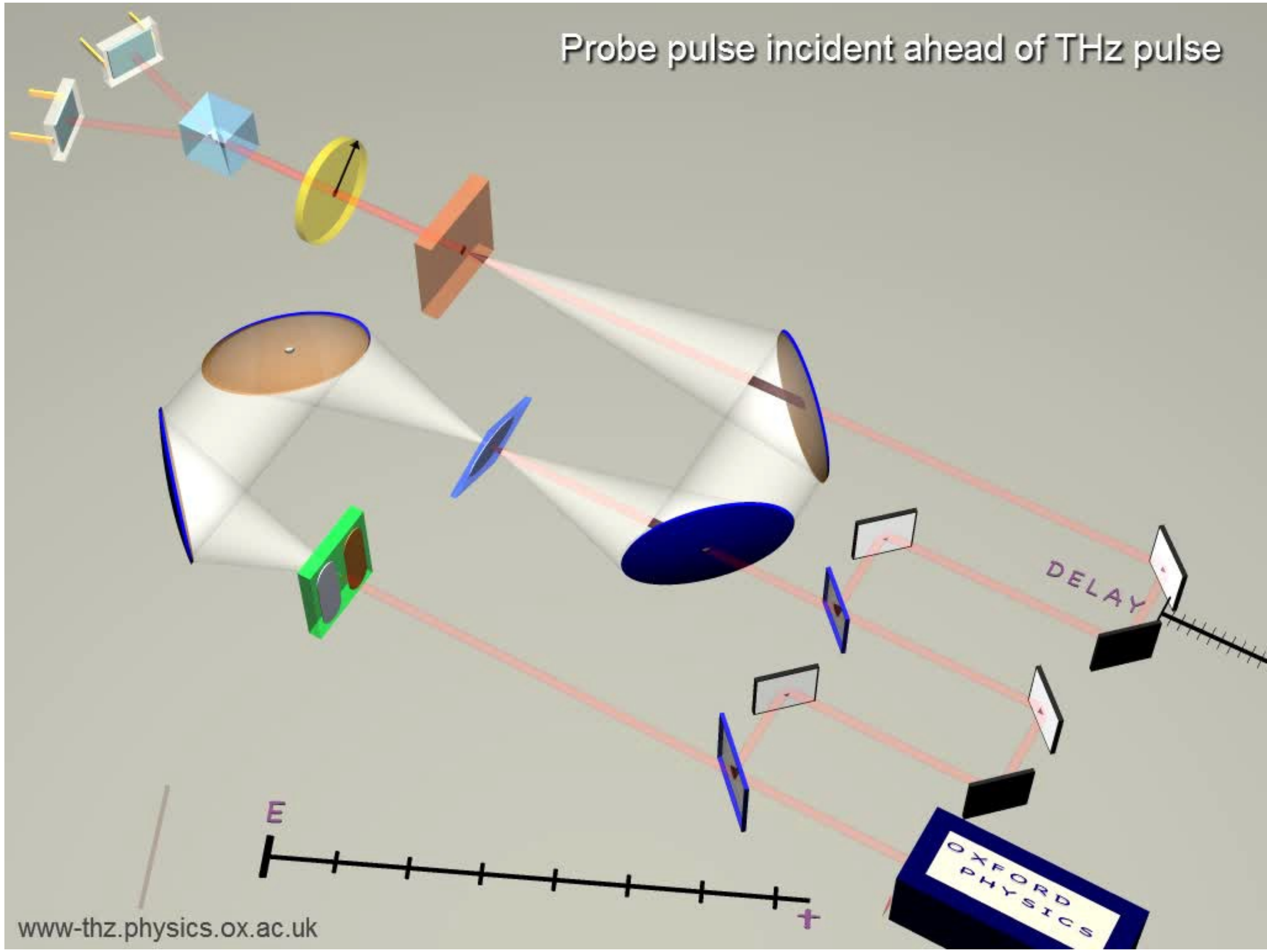
n-type GaAs nanowires



Review Article: *Semicond. Sci. Technol.* 31:103003 (2016)

THz photoconductivity spectroscopy
(Optical Pump THz Probe Spectroscopy)

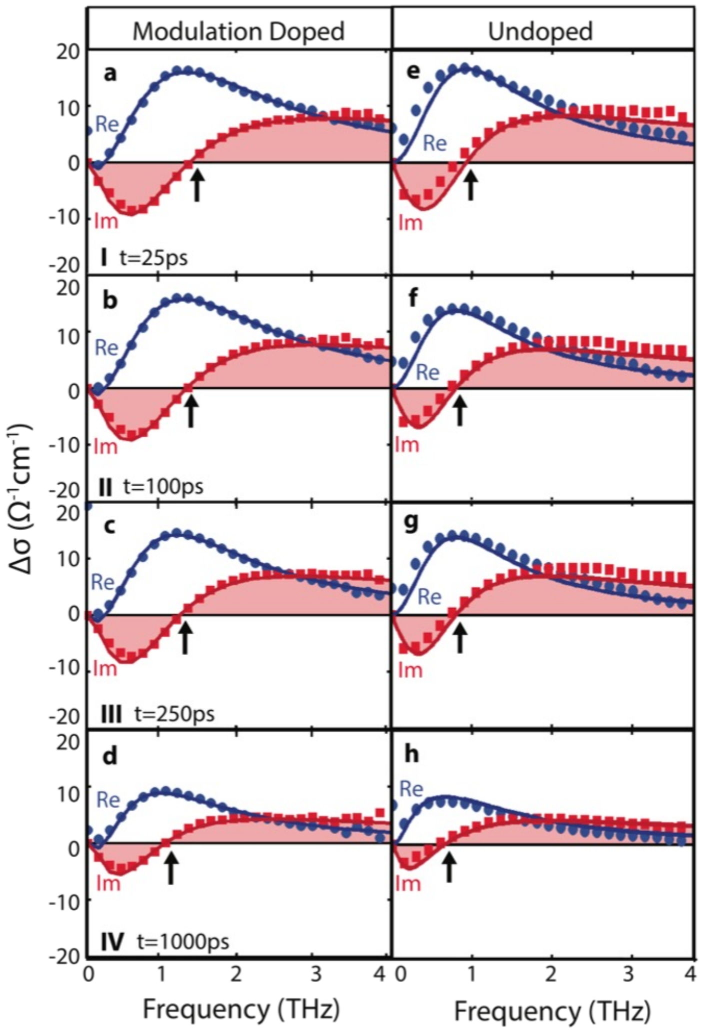




Review Article:
Semicond. Sci. Technol. 31:103003 (2016)

THz spectroscopy: a non-contact probe of nanowire electrical properties

Non-contact THz methods and models used to determine the key electrical properties of nanowires



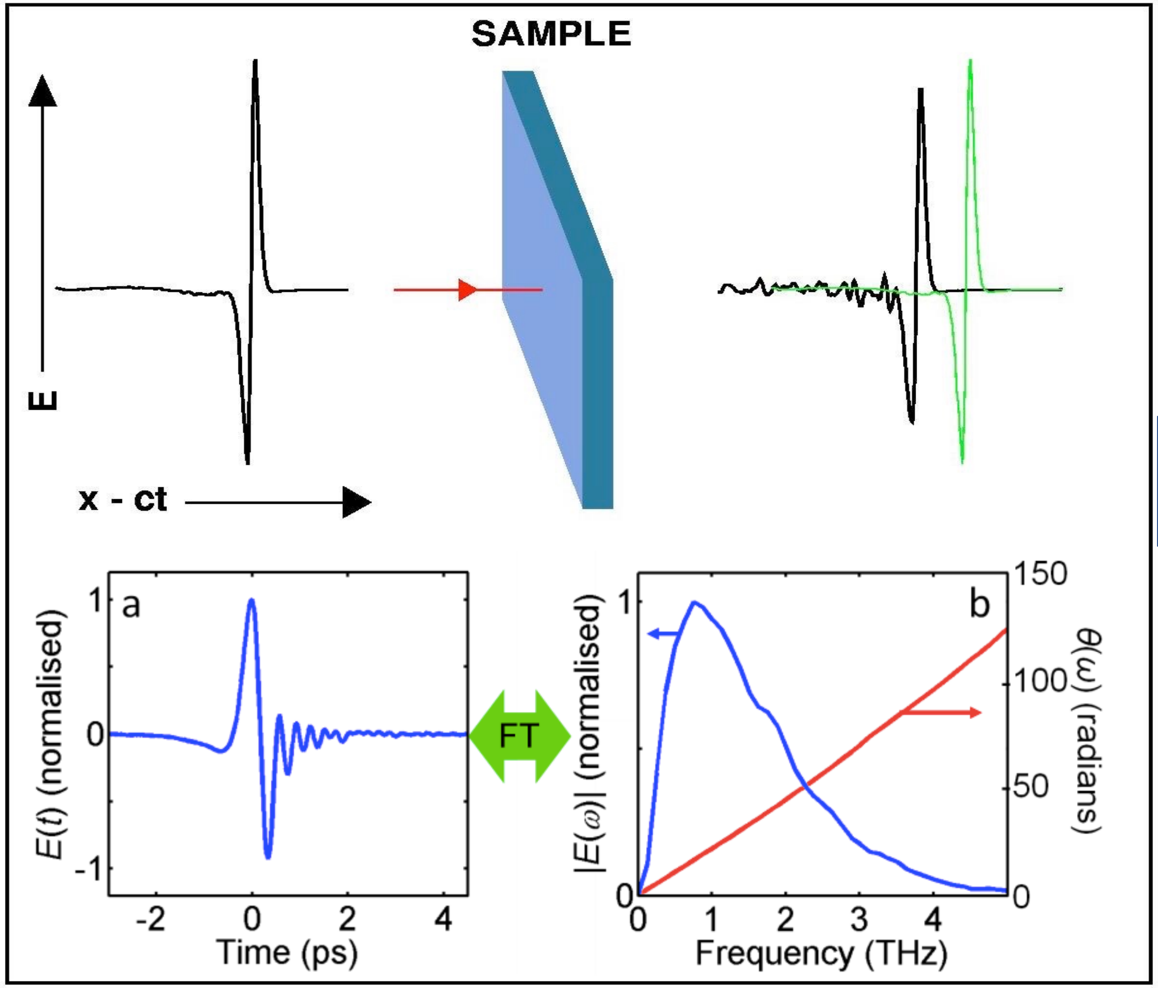
Past studies of semiconductor nanowires:

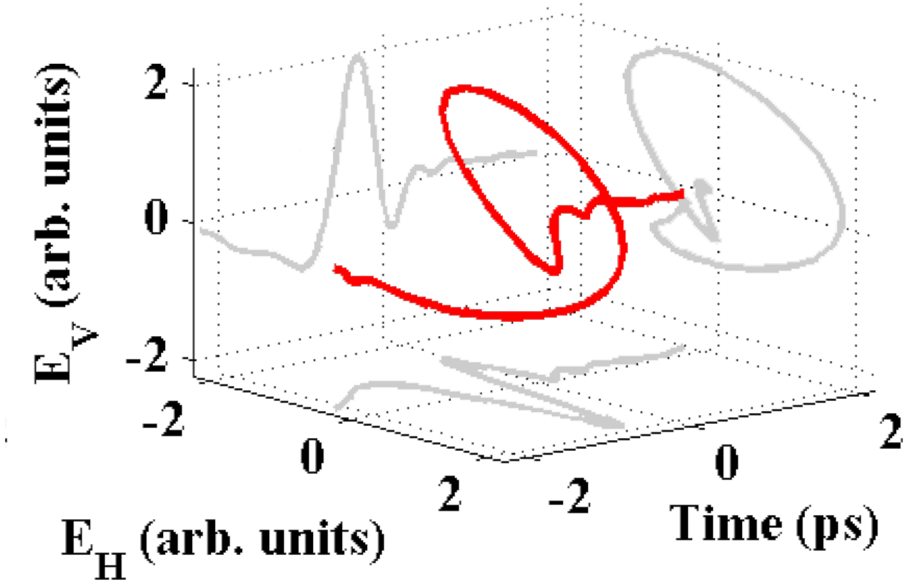
- Charge Carrier **Mobility**
  - *Nano. Lett.* **7**, 2162 (2007)
- **Doping density** and doping type
  - *ACS Nano*. **10**, 4219 (2016)
  - *Nano. Lett.* **15**, 1336 (2015)
- Charge Carrier **Lifetime**
  - *Nano. Lett* **9**, 3349 (2009)
- **Surface Recombination Velocity**
  - *Nano. Lett* **12**, 5325 (2012),
- **Donor binding energy measurement**
  - *Nanoscale* **9**, 7839 (2017),
- **Charge Scattering Mechanisms**
  - *Boland et al Nano Lett* (2018),

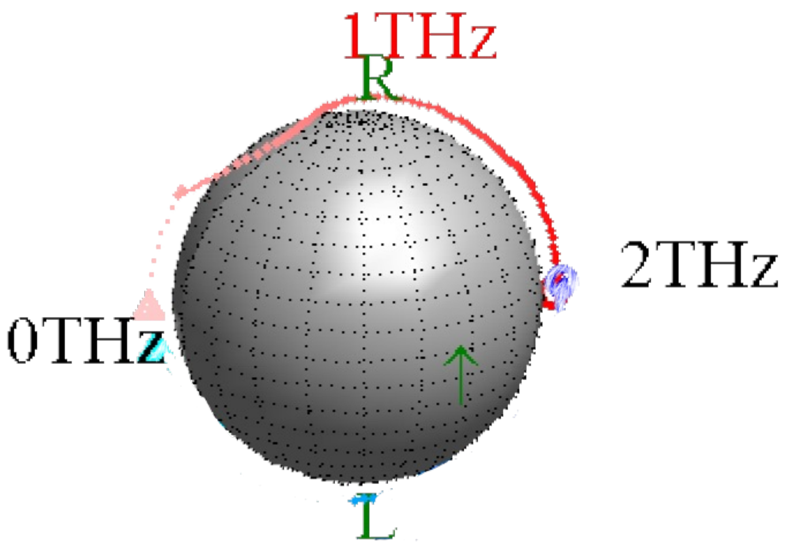
WE ARE NOW USING THIS KNOWLEDGE HELPS US DESIGN NANOWIRE DEVICES!!

Review Article: *Semicond. Sci. Technol.* 31:103003 (2016)

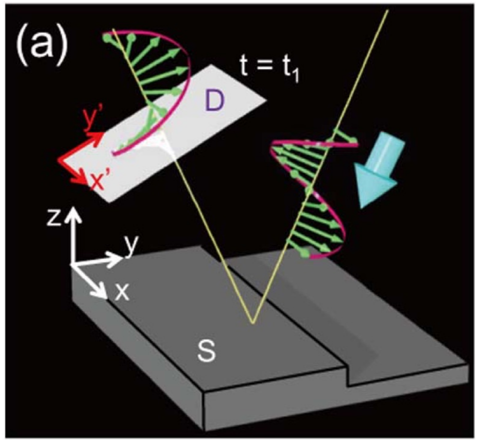
From Linearly Polarised to Arbitrarily Polarised THz pulses





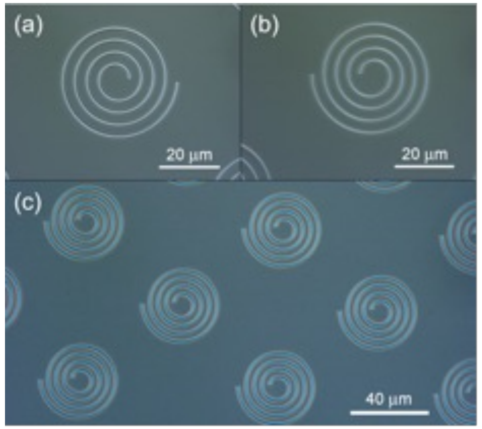


Applications of THz polarimetry

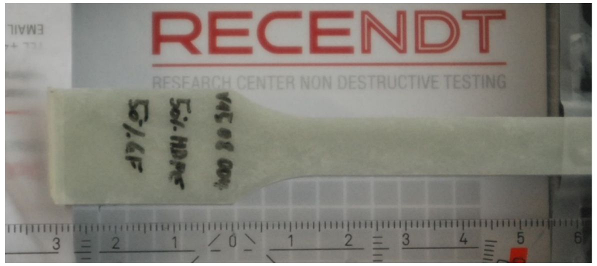


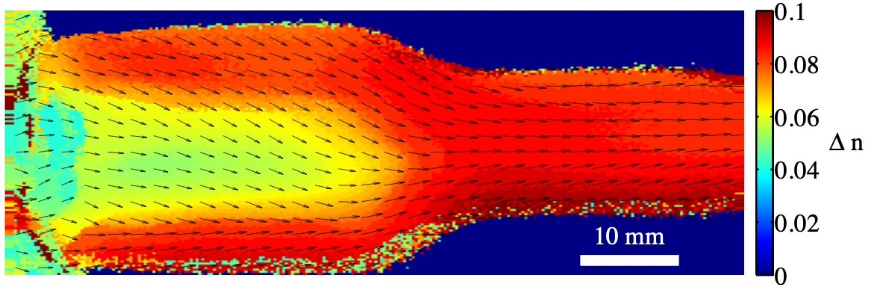
Optics Letters 37, 2706, 2012

- **THz Communications:** Signal encoding
- **THz Imaging** improved depth resolution and scatter suppression (e.g. Photonics 5, 58, 2018)
- **THz Birefringence Imaging:** i.e. map anisotropy / stress / strain in materials (Optics Express 20, 23025, 2012)
- **Plasma Diagnostics** e.g. cyclotron magnetic field mapping
- **THz Hall Effect and Cyclotron resonance** for materials characterisation (e.g. Mittleman, *Appl. Phys. Lett.* **71**, 16, 1997, Matsuda, *Nat Commun* **11,** 909, 2020)
- **Faraday rotation spectroscopy**
- **THz ellipsometry** for determining dielectric properties of materials
- **Vibrational circular dichroism** biological systems (Appl. Phys. Lett. 100, 241114, 2012)



Appl. Phys. Lett. 100, 241114, 2012





Optics Express 20, 23025, 2012

Time resolved cyclotron resonance in InSb

THz cyclotron resonance

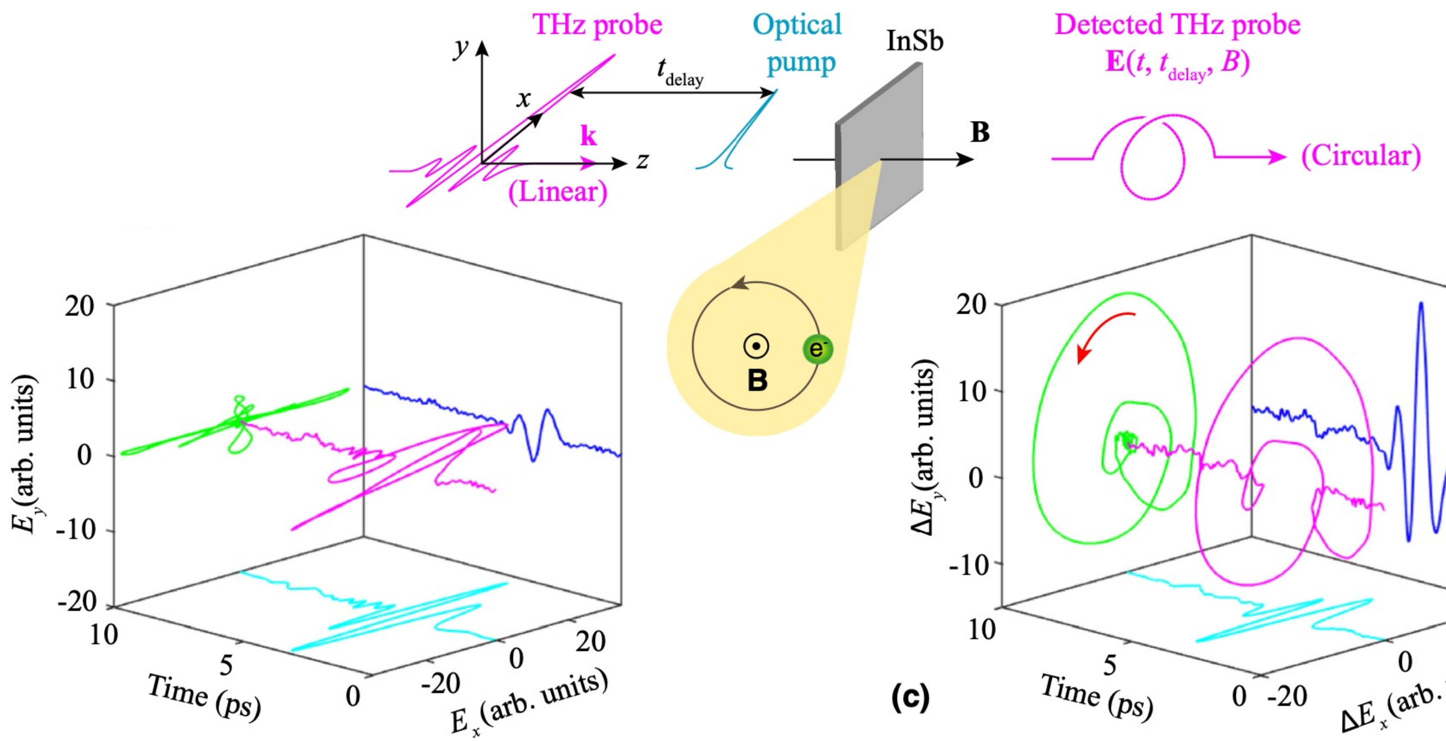
$$J_i = \sigma_{ij} E_j$$

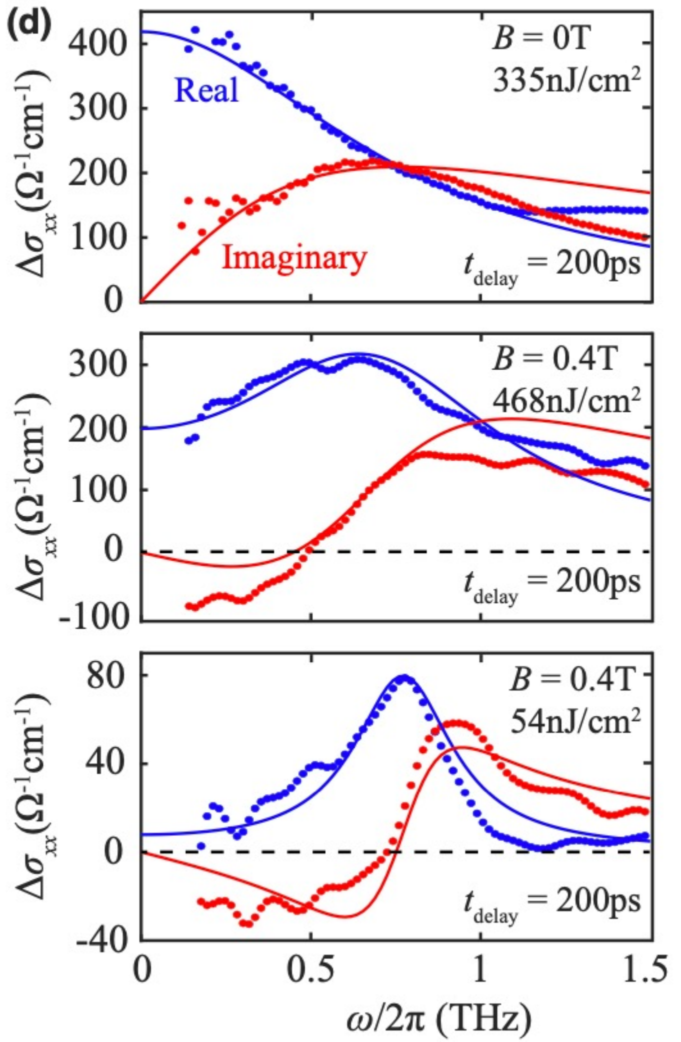
for $B_z \neq 0$ in the Drude relaxation time approx

$$\Delta\sigma_{ij}(\omega) = \frac{\sigma_0}{(1 - i\omega\tau)^2 + (\omega_c\tau)^2}\begin{bmatrix} 1 - i\omega\tau & -\omega_c\tau \\ \omega_c\tau & 1 - i\omega\tau \end{bmatrix} \qquad \omega_c = \frac{eB}{m^*}$$

$$\Delta\sigma_{xx}(\omega) = -\varepsilon_0 c\alpha(1 + \tilde{n})\left[\frac{\Delta E_x(\omega, B)}{E_x^{\mathrm{dark}}(\omega, B)}\right]$$

InSb epilayer 4K

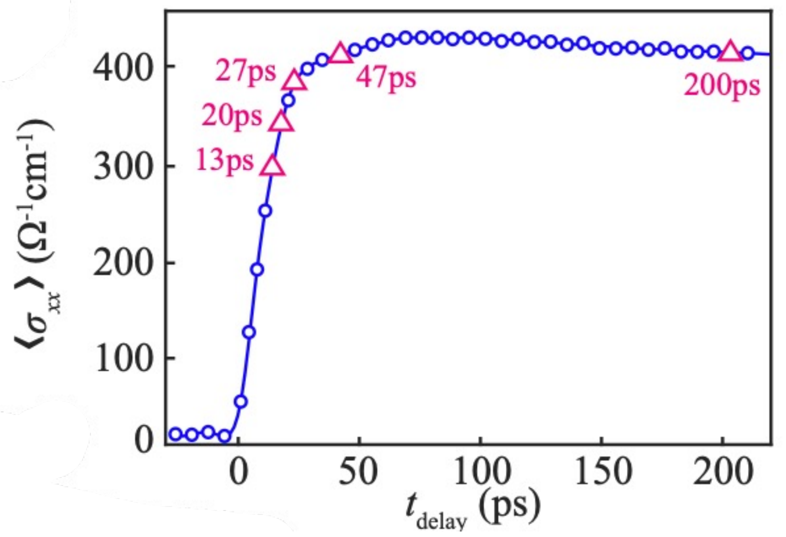


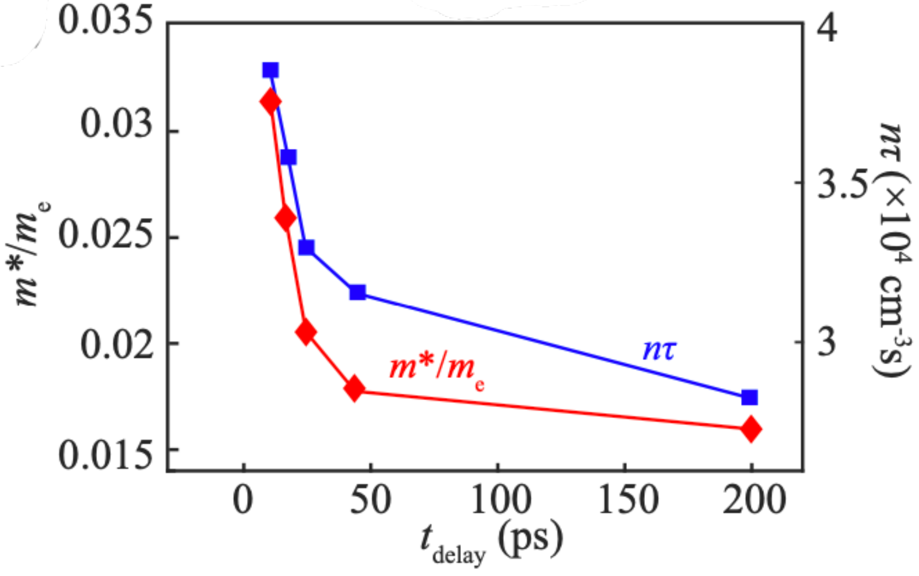


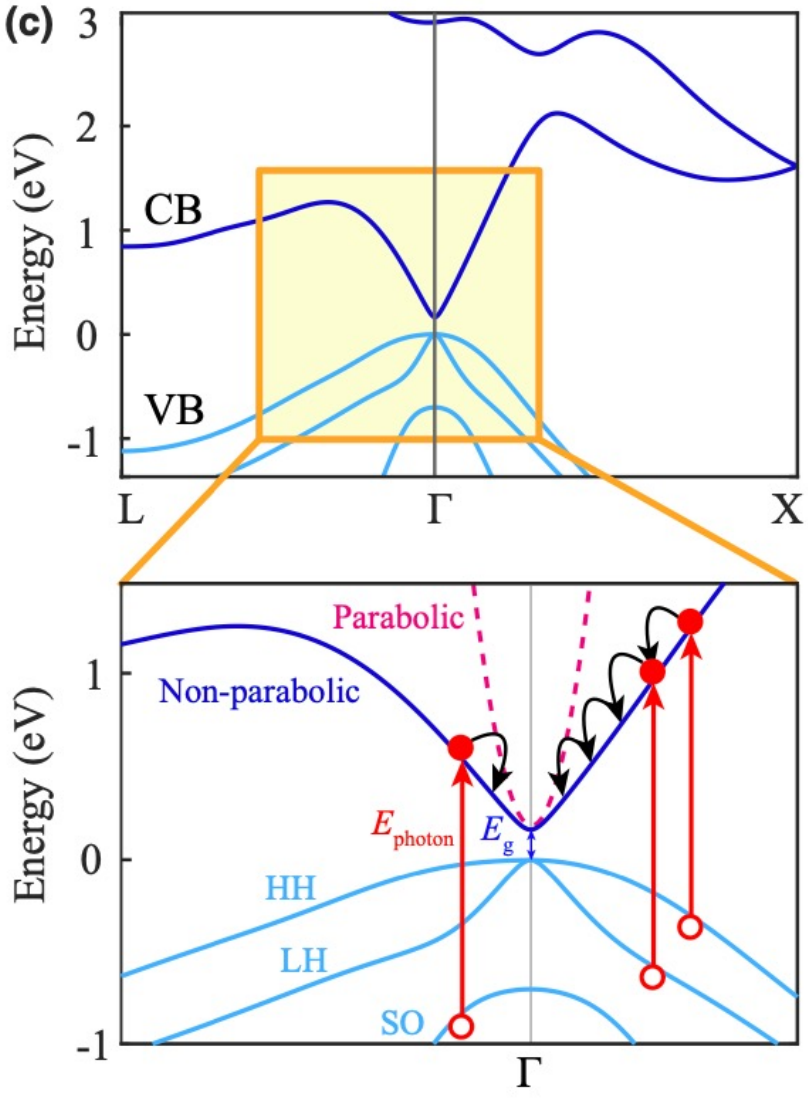
Xia et al., Phys Rev B 103, 245205 (2021).

Time resolved cyclotron resonance in InSb

InSb epilayer 4K

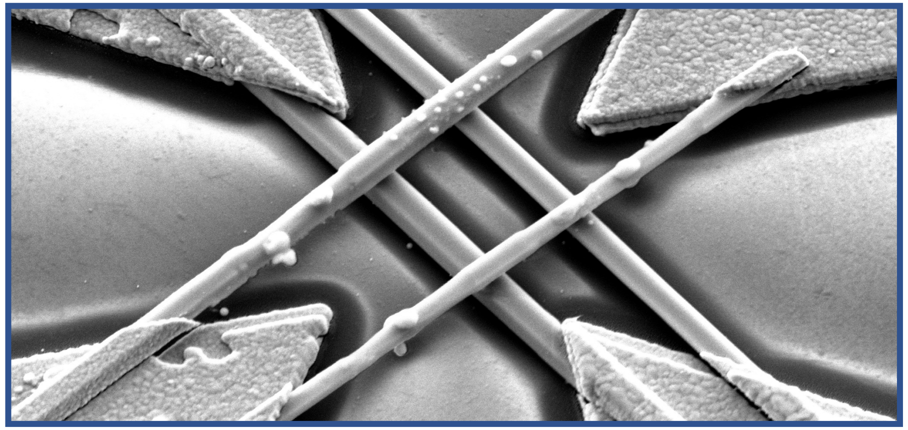






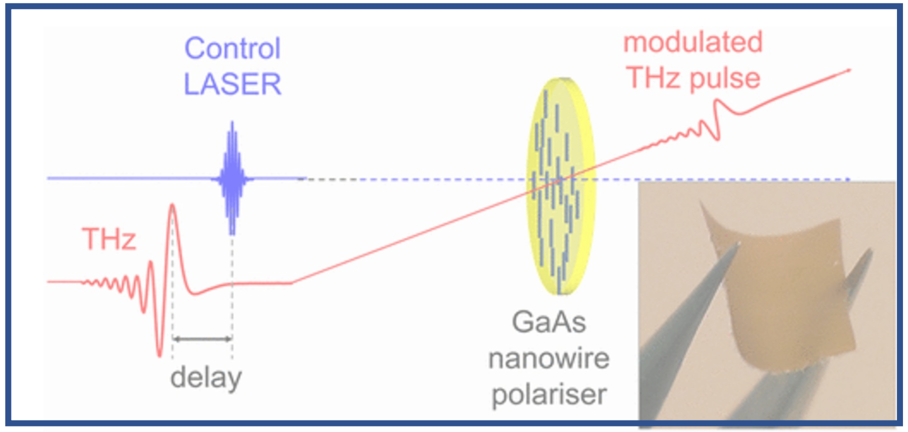
Xia et al., Phys Rev B 103, 245205 (2021).

Nanowire Devices for THz polarimetry



1. Cross-nanowire THz detector for extracting the full polarisation state of THz pulses

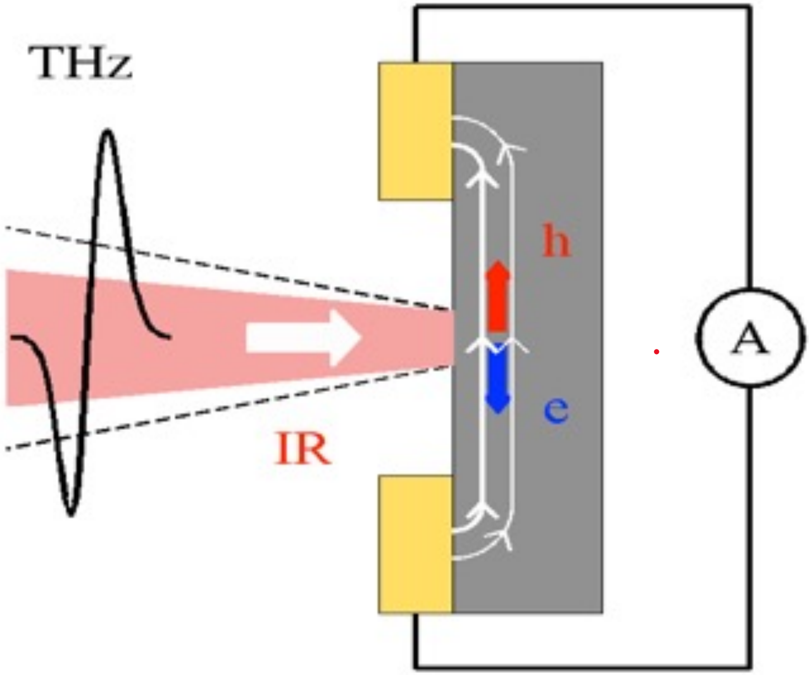
Science, **368**:510--513 (2020)

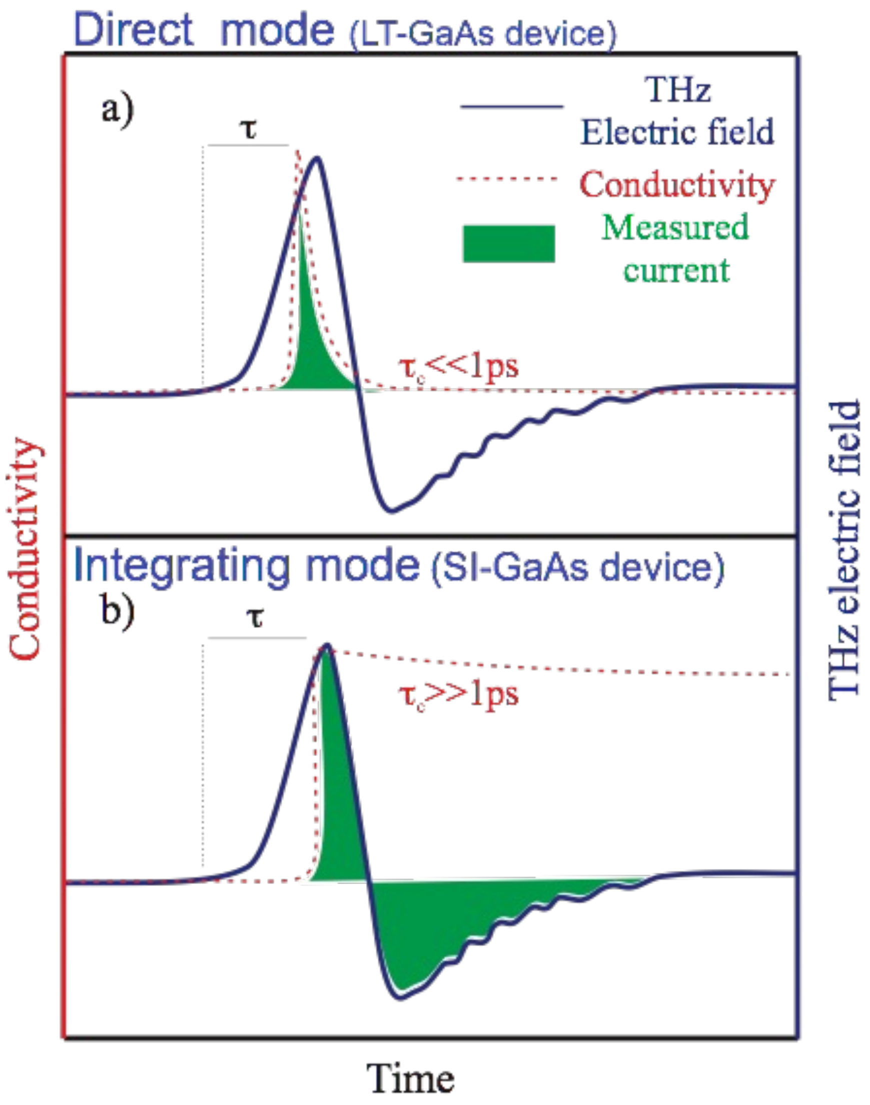


2. Ultrafast, broadband modulator of THz radiation (~ps switching speed)

Nano Lett., 17:2603 (2017)
Tuomas Haggren, Unpublished

Background: How THz Photoconductive detectors / Auston switches work



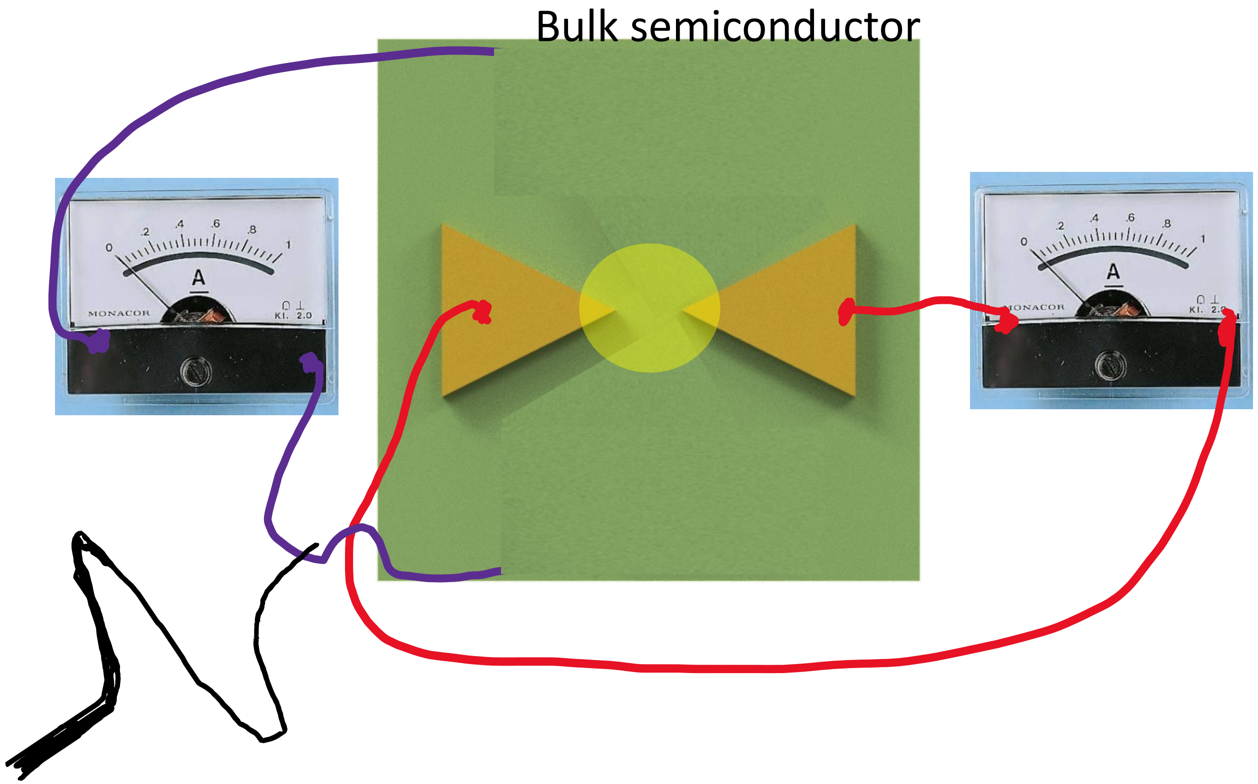


Detector optimisation(e.g. SNR) requires control over charge carrier dynamics
- usually ion implanted
- low temperature grown GaAs, InGaAs

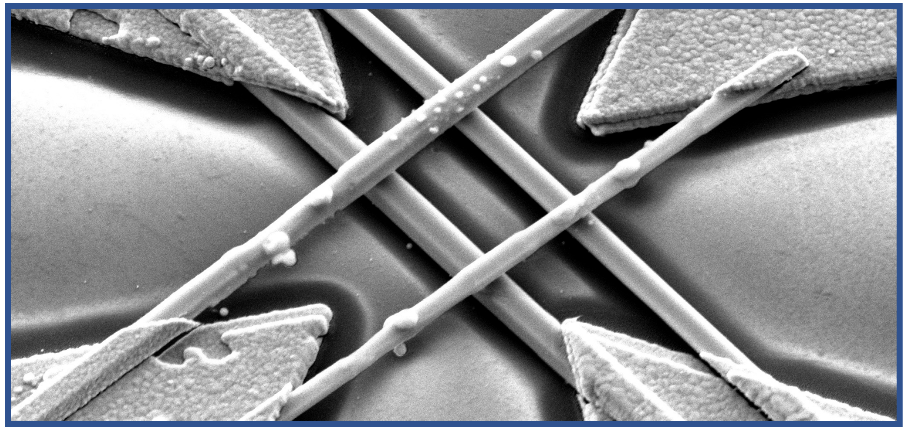
- Original concept - Auston, Cheung & Smith Appl. *Phys. Lett. 45:284, 1984*
- Theory of THz PC detection *J. Appl. Phys.*, 104, 053113, 2008
- First polarisation receiving THz detectors *APL* 86, 254102, 2005 (GaAs) & *Optics Express* 15, 7047, 2007 (InP:Fe+)
- Theory of dielectric response extraction from polarisation resolving THz sensors*: J Opt A Pure Appl Opt*, 11, 105206, 2009

Multi-contact Polarisation resolving THz detectors

- ✓ Compact
- ✓ Monlithic
- ✓ Compatible with most existing THz-TDS systems
- ✗ Cross-talk between orthogonal channels
- ✗ Difficult to align
- ✗ Lack of sensitivity

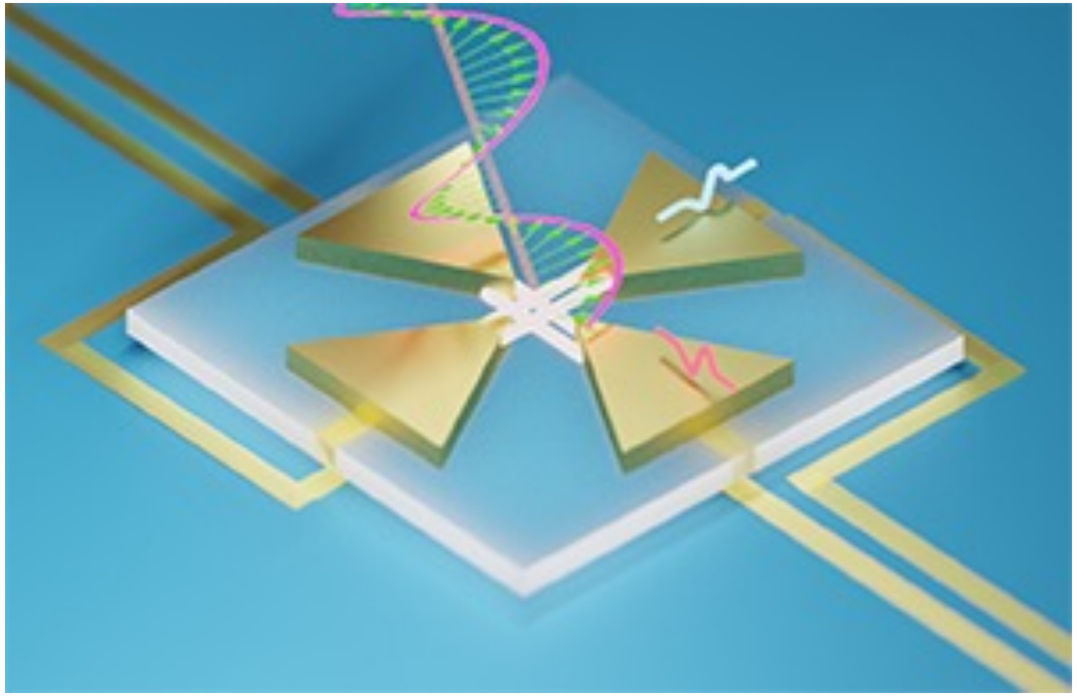


Nanowire Devices for THz polarimetry



Cross-nanowire THz detector for extracting the full polarisation state of THz pulses

Science, **368**:510--513 (2020)

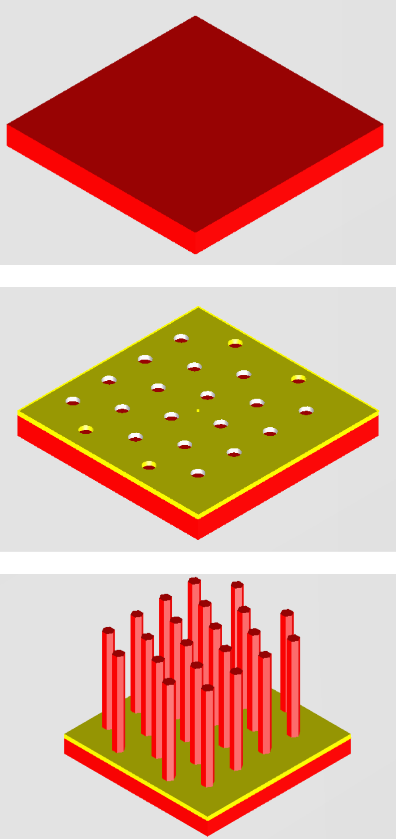


Nanowires allow us to have

- ✓ An optimised polarisation selective antenna
- ✓ Complete electrical isolation between orthogonal channels
- ✓ Very compact device

InP Nanowires Grown by Selective Area Epitaxy (SAE)

SA-MOVPE



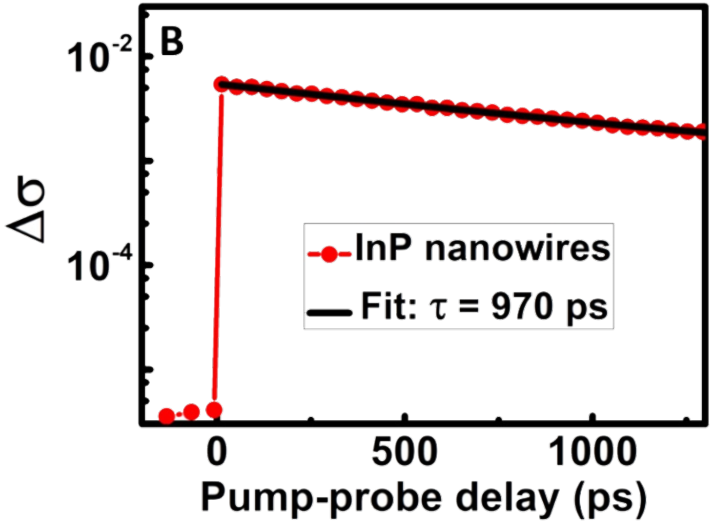
- Catalyst free nanowires

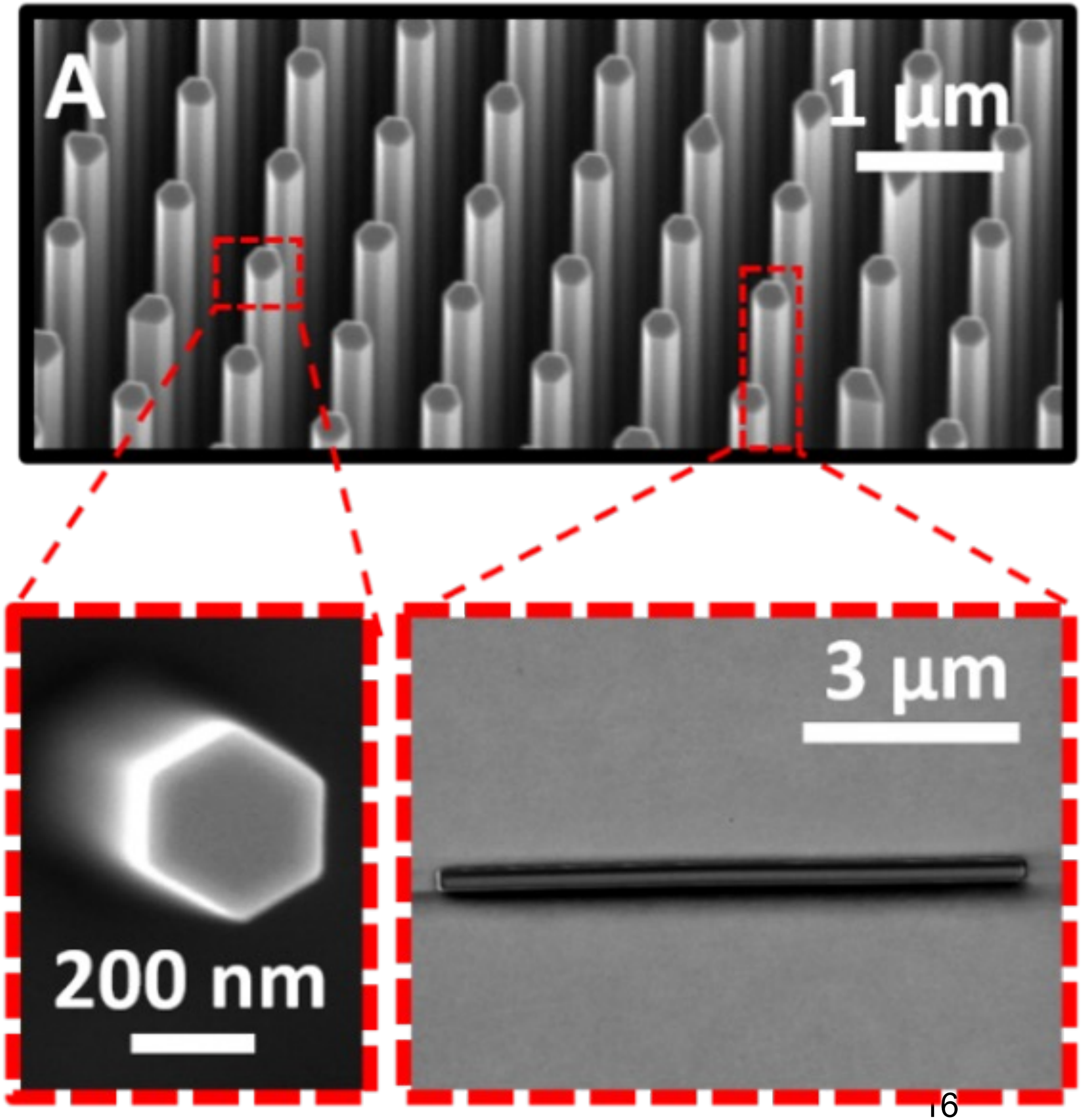
Australian National University

Why InP nanowires?

- Direct bandgap
- High Electron Mobility
- High Radiative Quantum Efficiency
- Low density of surface state

- ➢ Stacking-fault-free
- ➢ Pure Wurtzite
- ➢ Structurally uniform
- ➢ Diameters ~200 nm and lengths 8 -11 μm





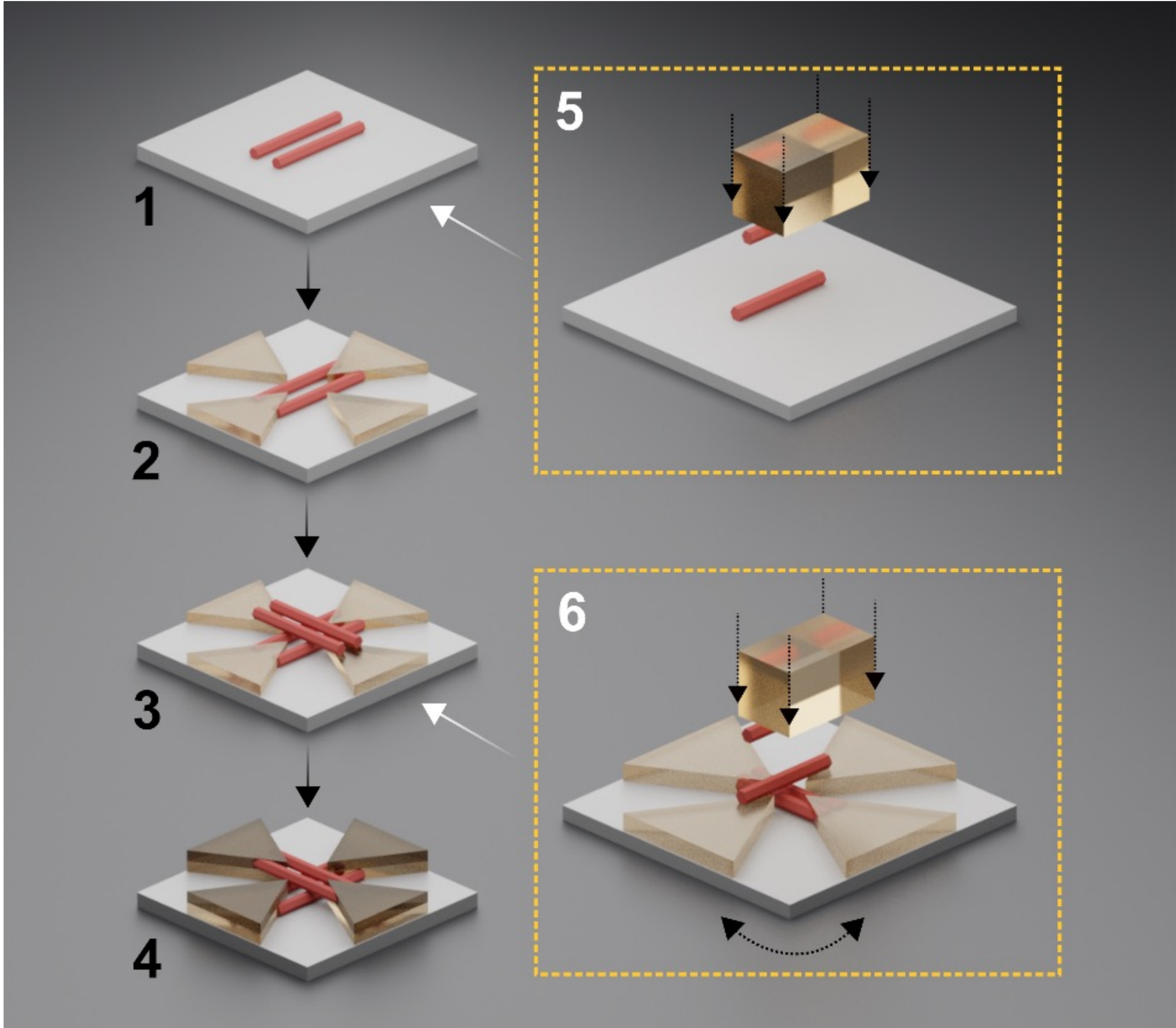
Science, **368**:510--513 (2020)

Cross-Nanowire detector fabrication

Nanowires positioned using Transfer Printing

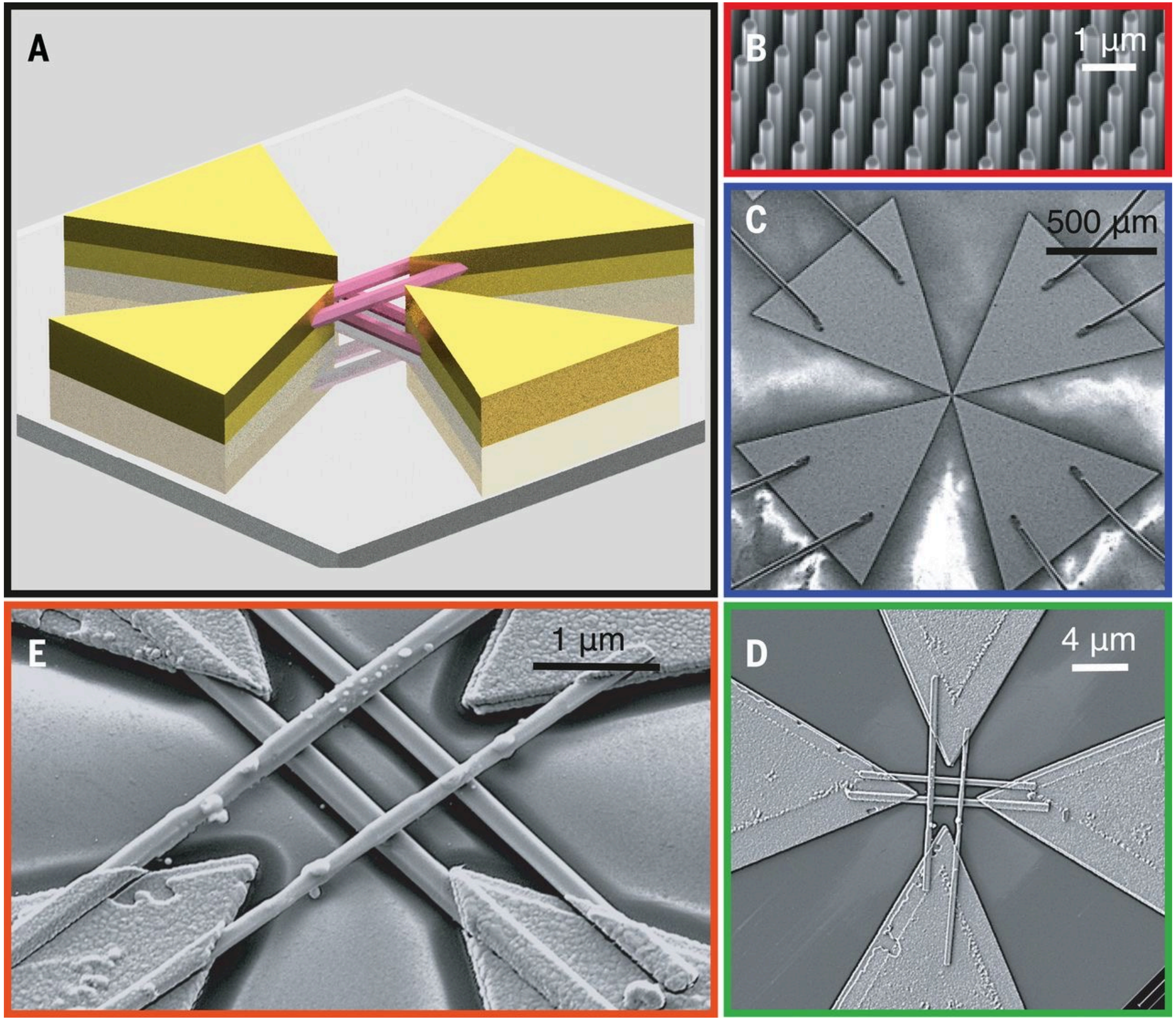
ACS Nano 10, 3951 (2016)

University of Strathclyde Glasgow



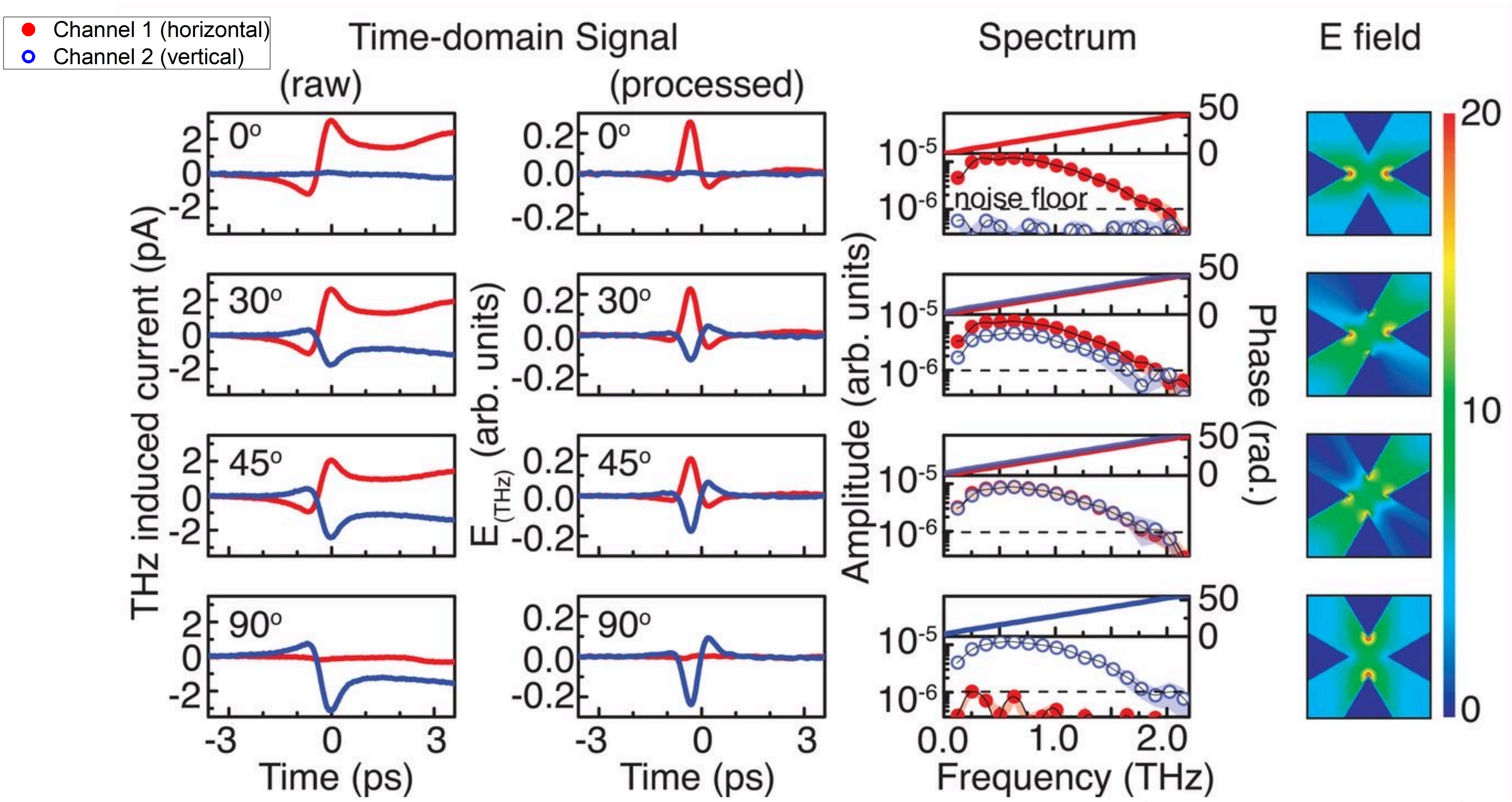
Science, **368**:510--513 (2020)

Cross-nanowire THz detector



Peng et al
Science, **368**:510-513 (2020)

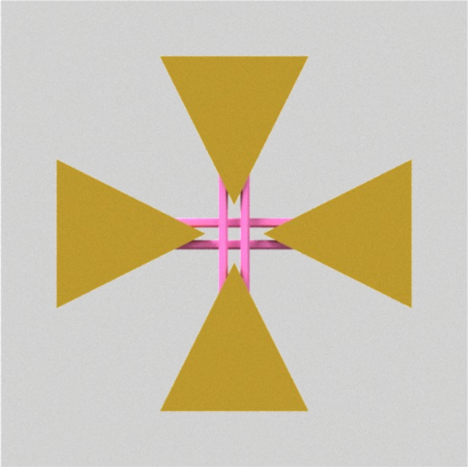
Cross-nanowire THz Detector Characterisation

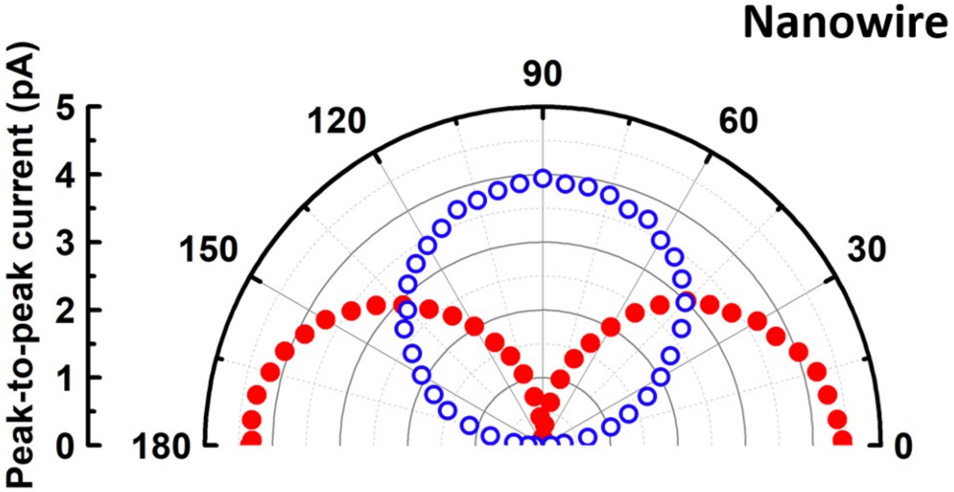


Peng et al., Science 368, 510-513 (2020).

Cross-nanowire THz Detector Characterisation

Nanowire 4-contact

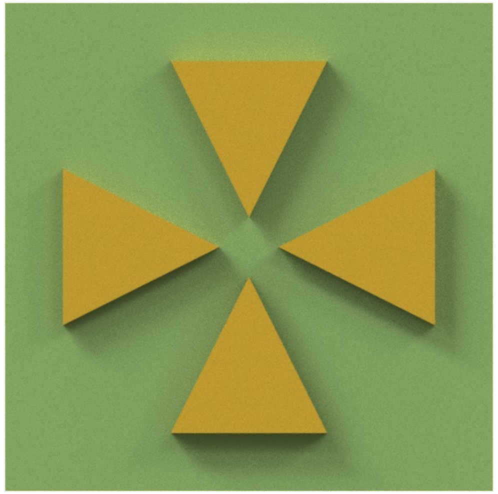




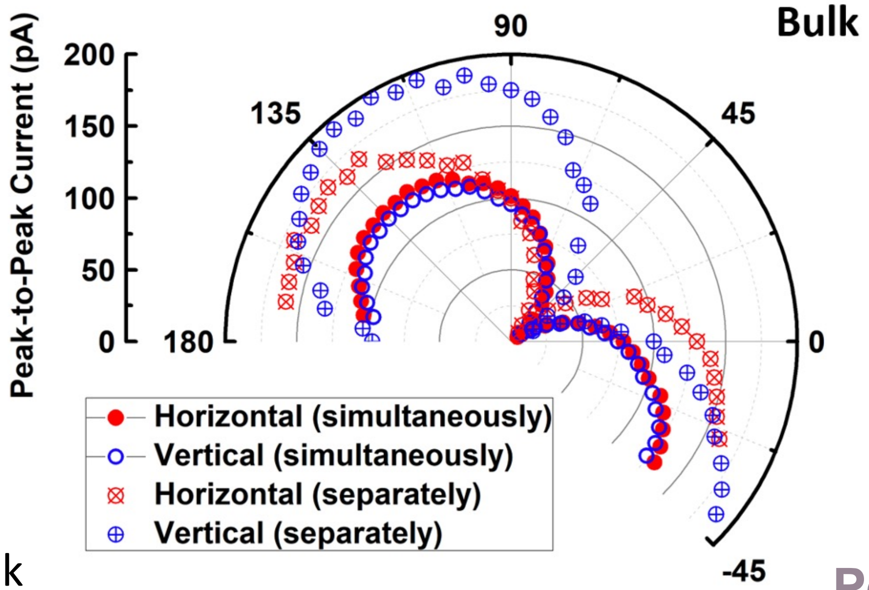
extinction ratio:
2500 for Channel 1
1440 for Channel 2

minimum detectable change of polarization angle is 0.38°

Bulk 4-contact



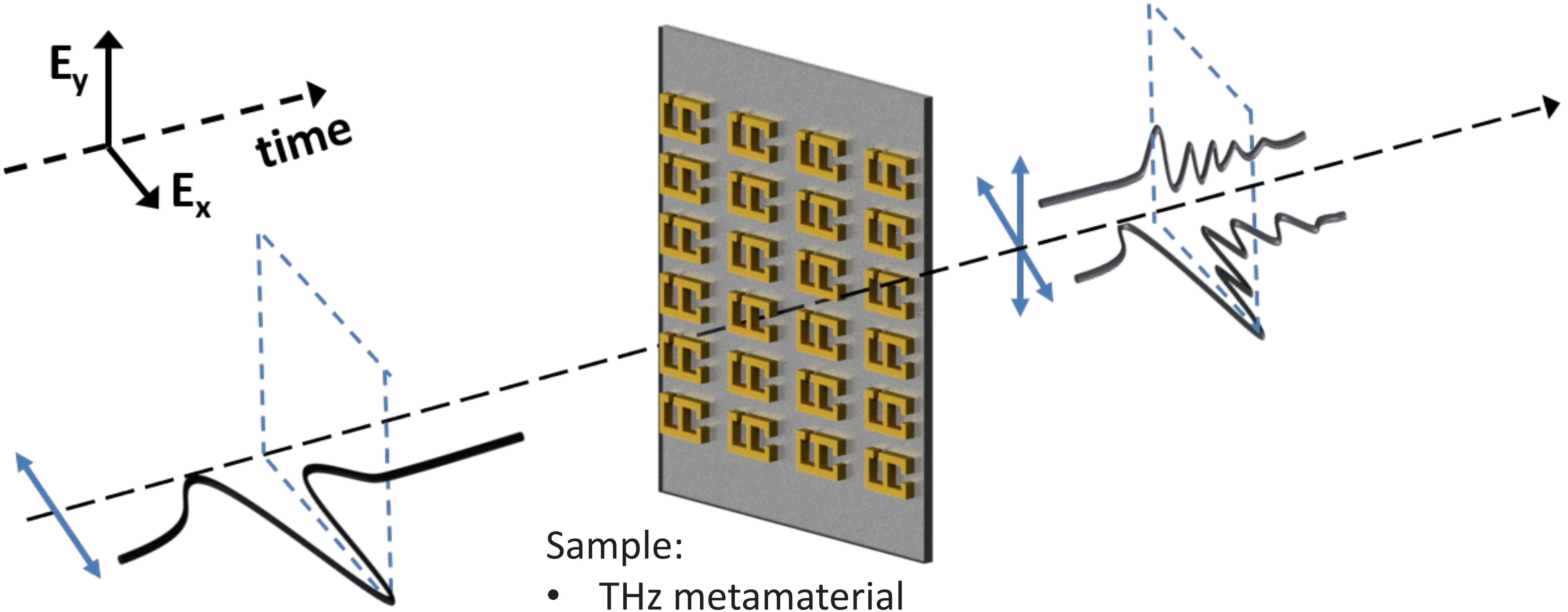
Detection dominated by crosstalk



Electrical Crosstalk Eliminated for nanowire device!

Peng et al., Science 368, 510-513 (2020).

Spectroscopy with the cross-nanowire THz detector

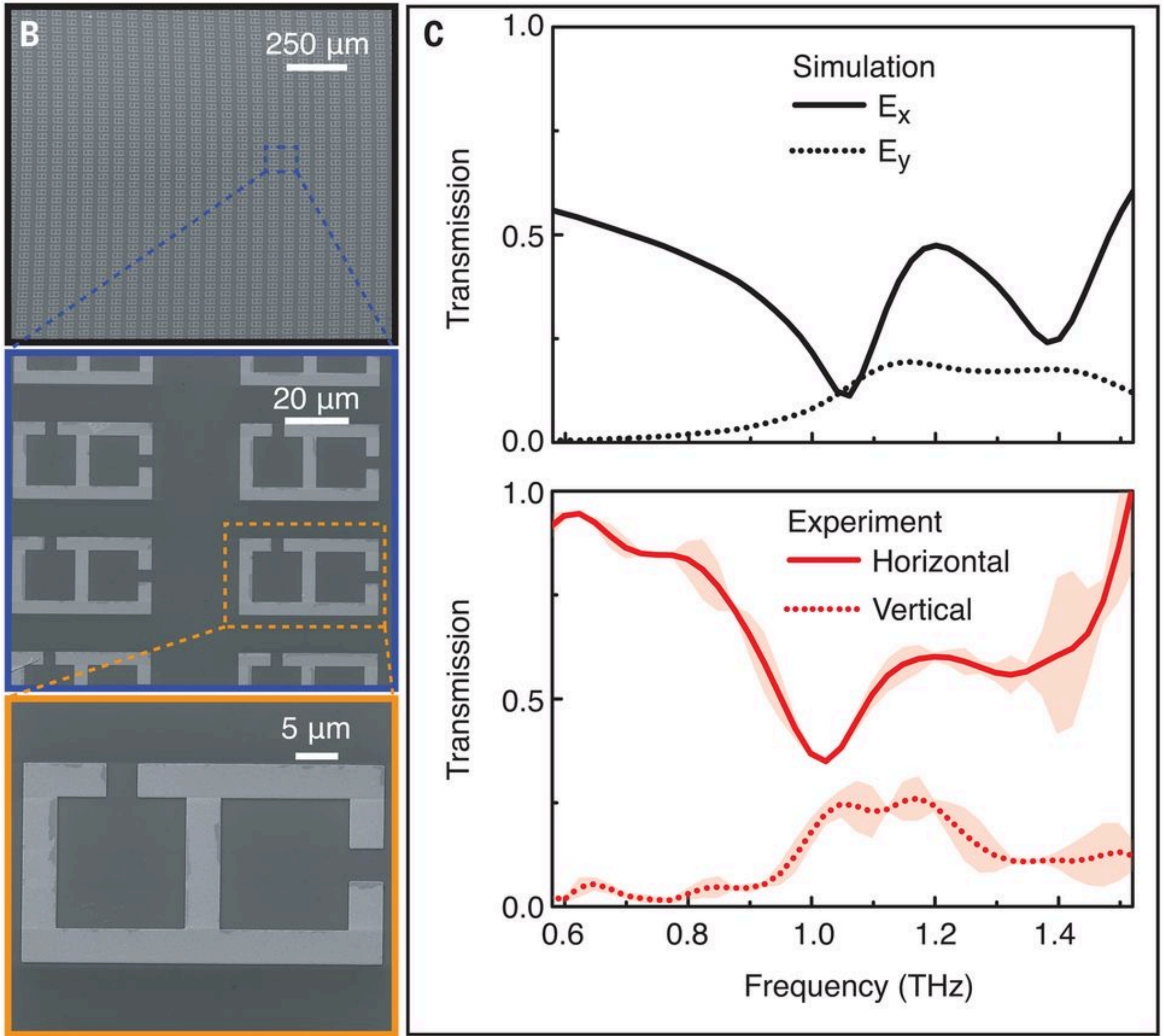


Sample:

- THz metamaterial
- Gold pattern on quartz
- Twisted split-ring resonator pair
- Designed to function as a polarization converter

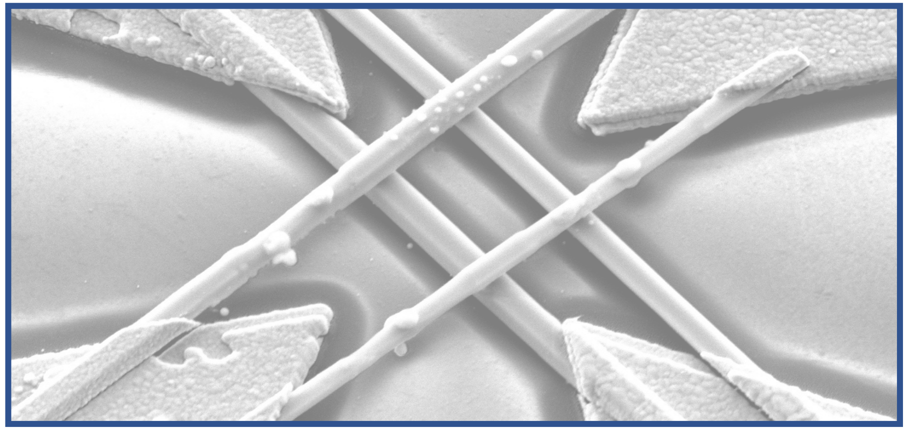
Peng et al., Science 368, 510-513 (2020).

Cross-nanowire THz detector



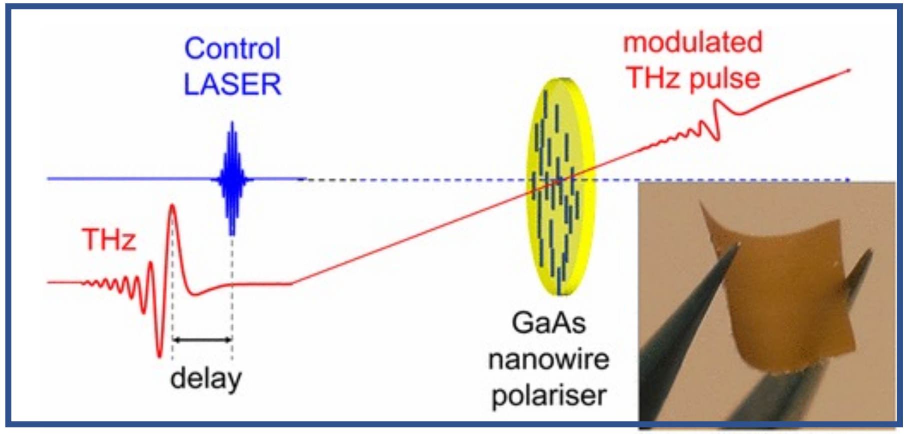
Peng et al., Science 368, 510-513 (2020).

Nanowire Devices for THz polarimetry



1. Cross-nanowire THz detector for extracting the full polarisation state of THz pulses

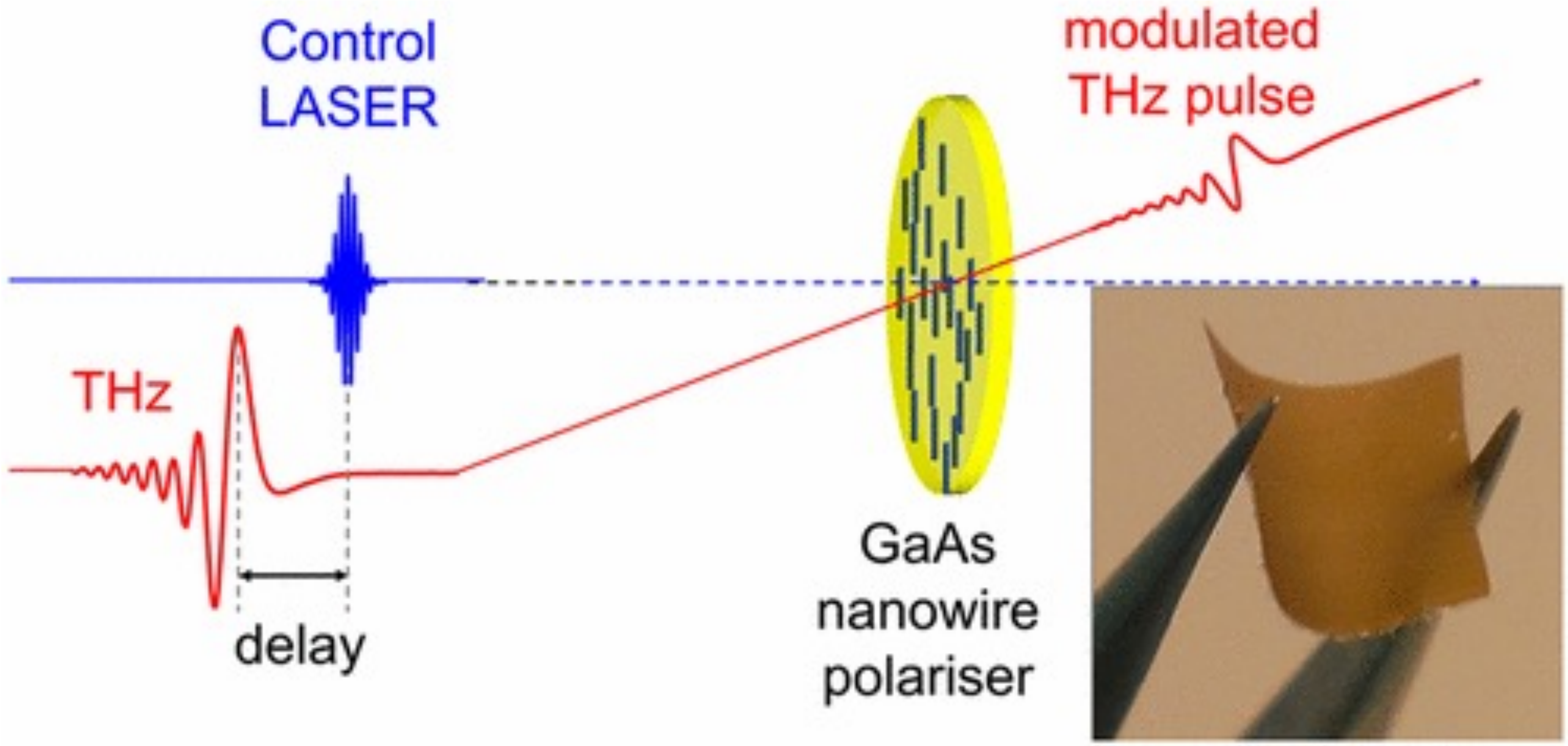
Science, **368**:510--513 (2020)



2. Ultrafast, broadband modulator of THz radiation (~ps switching speed)

Nano Lett., 17:2603 (2017)
Tuomas Haggren, Unpublished

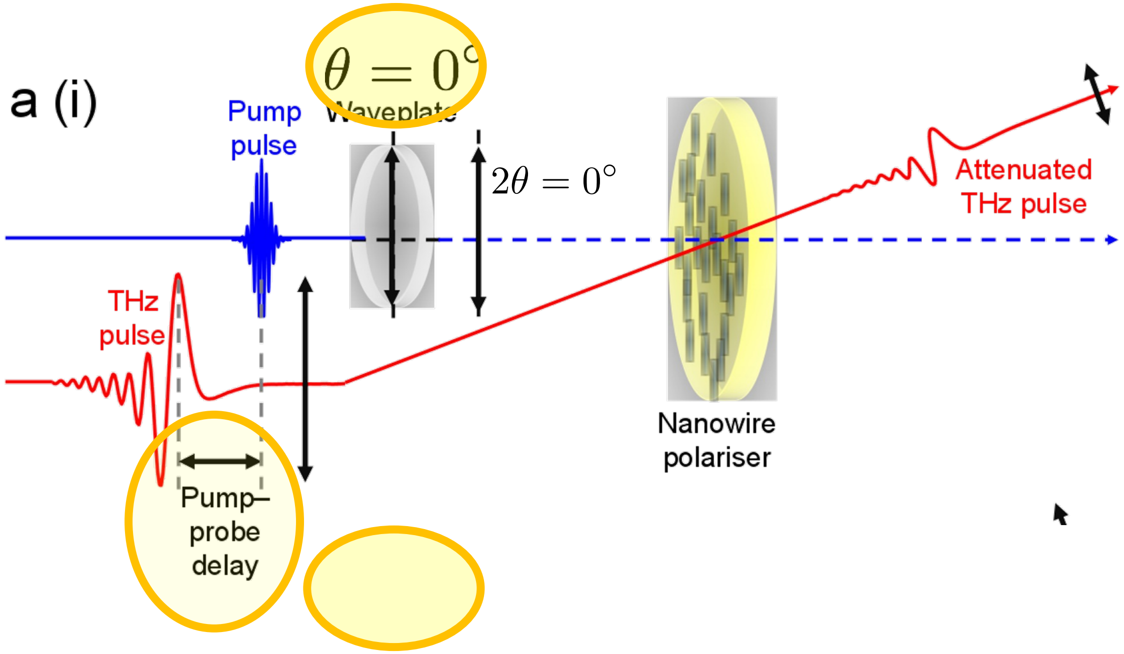
Nanowire-Based THz Modulator - Concept



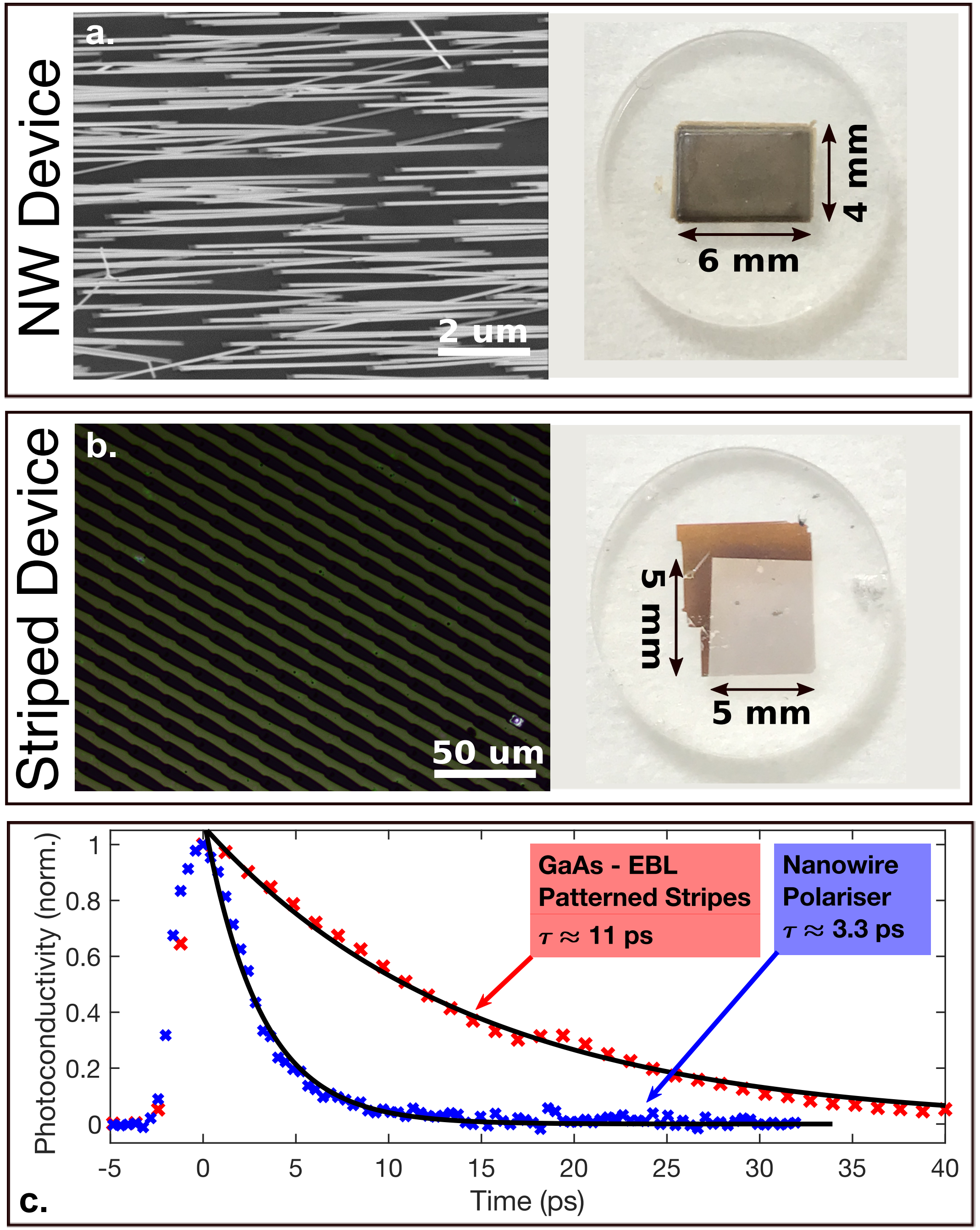
Switchable wire-grid polariser

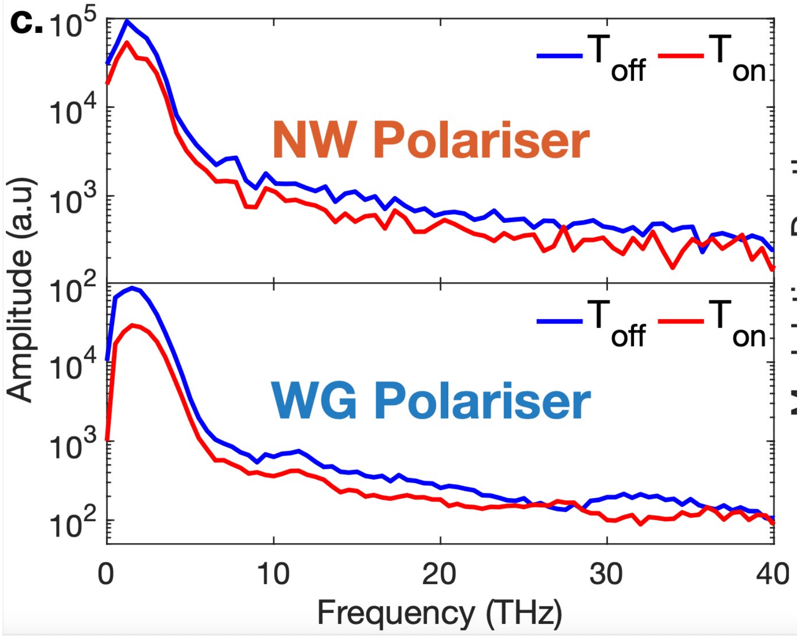
Baig et al. *Nano Lett.* 17:2603 (2017)

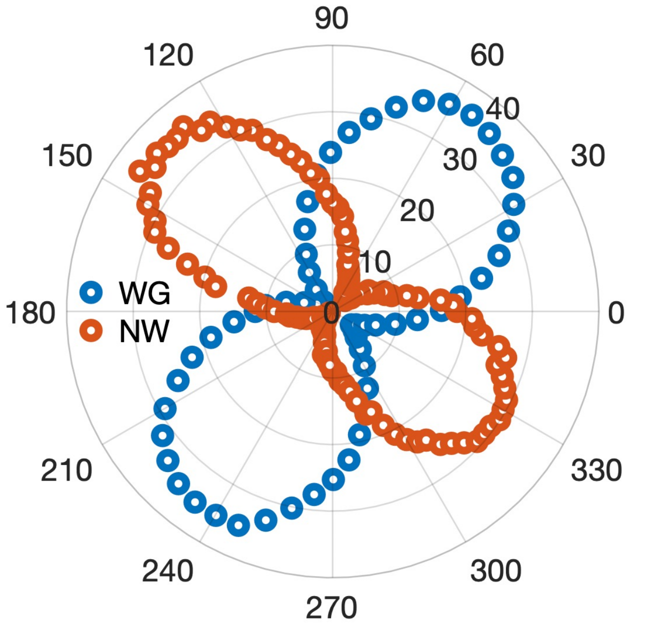
Nanowire-Based THz Modulator – Testing



Baig et al. *Nano Lett.* 17:2603 (2017)







Unpublished

Acknowledgements

Oxford Dr Kun Peng, Sabrina Sterzl, Djamshid A Damry, Dr Mathias U Rothmann, Prof Laura M Herz

Australian National University Fanlu Zhang, Prof Hoe Tan, Prof. Lan Fu Prof. Chennupati Jagadish

University of Strathclyde Dimitars Jevtics, Benoit Guilhabert, Michael J Strain, Martin D Dawson Dr. Antonio Hurtado

University of Cambridge Sarwat Baig, Dr Hannah Joyce

- Peng, Jevtics, Zhang, Sterzl, Damry, Rothmann, Guilhabert, Strain, Tan, Herz, Fu, Dawson, Hurtado, Jagadish, Johnston *Science*, **368**:510--513 (2020)
- Peng, Johnston, *Appl. Phys. Rev.* ***8***:041314 (2021)
- SA Baig, JL Boland, DA Damry, HH Tan, C Jagadish, HJ Joyce, MB Johnston *Nano Lett.*, **17**:2603 (2017)
- Xia et al *Phys Rev B* **103:**245205 (2021)

www-thz.physics.ox.ac.uk

TMOS
ARC CENTRE OF EXCELLENCE FOR TRANSFORMATIVE META-OPTICAL SYSTEMS

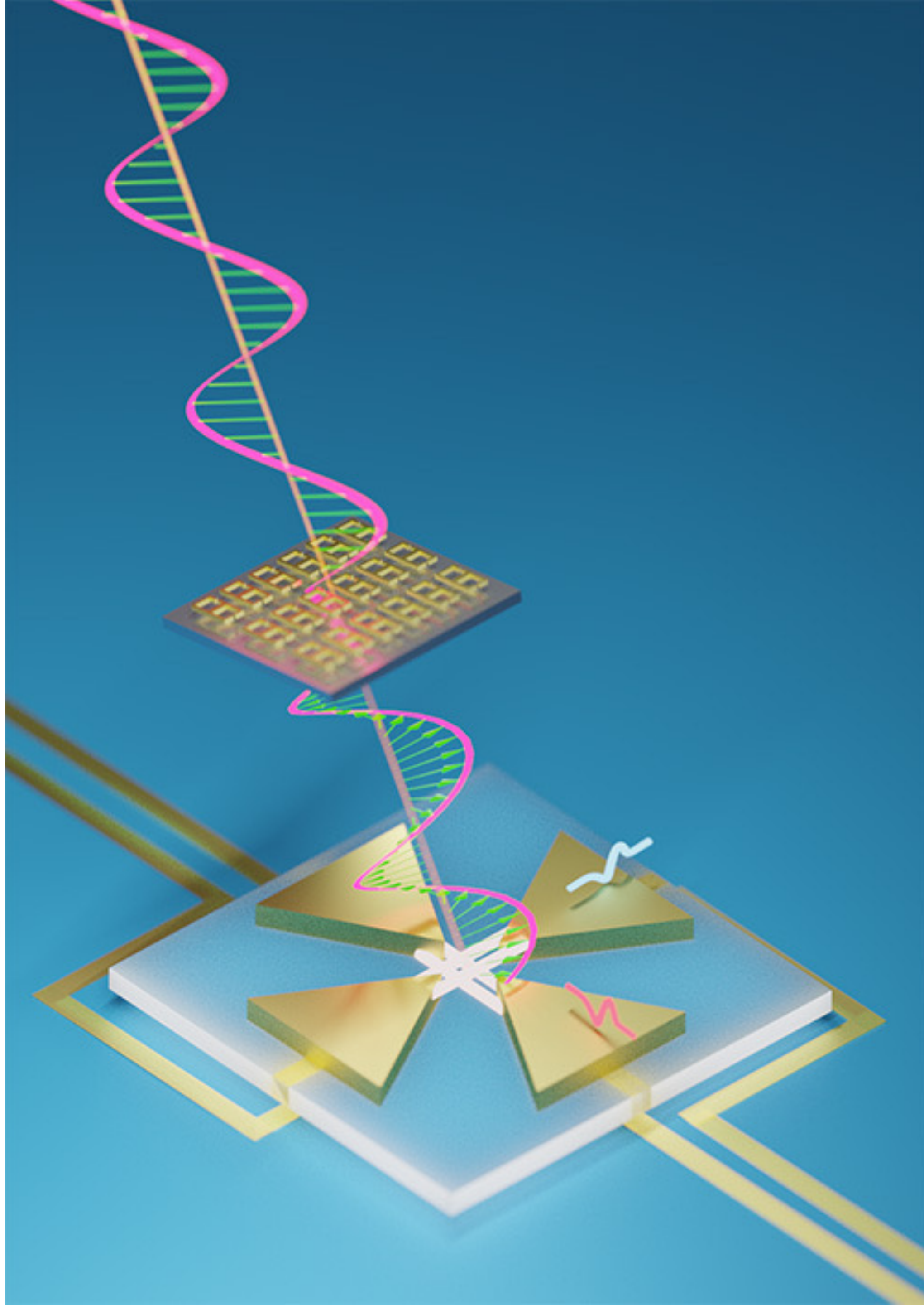
European Commission

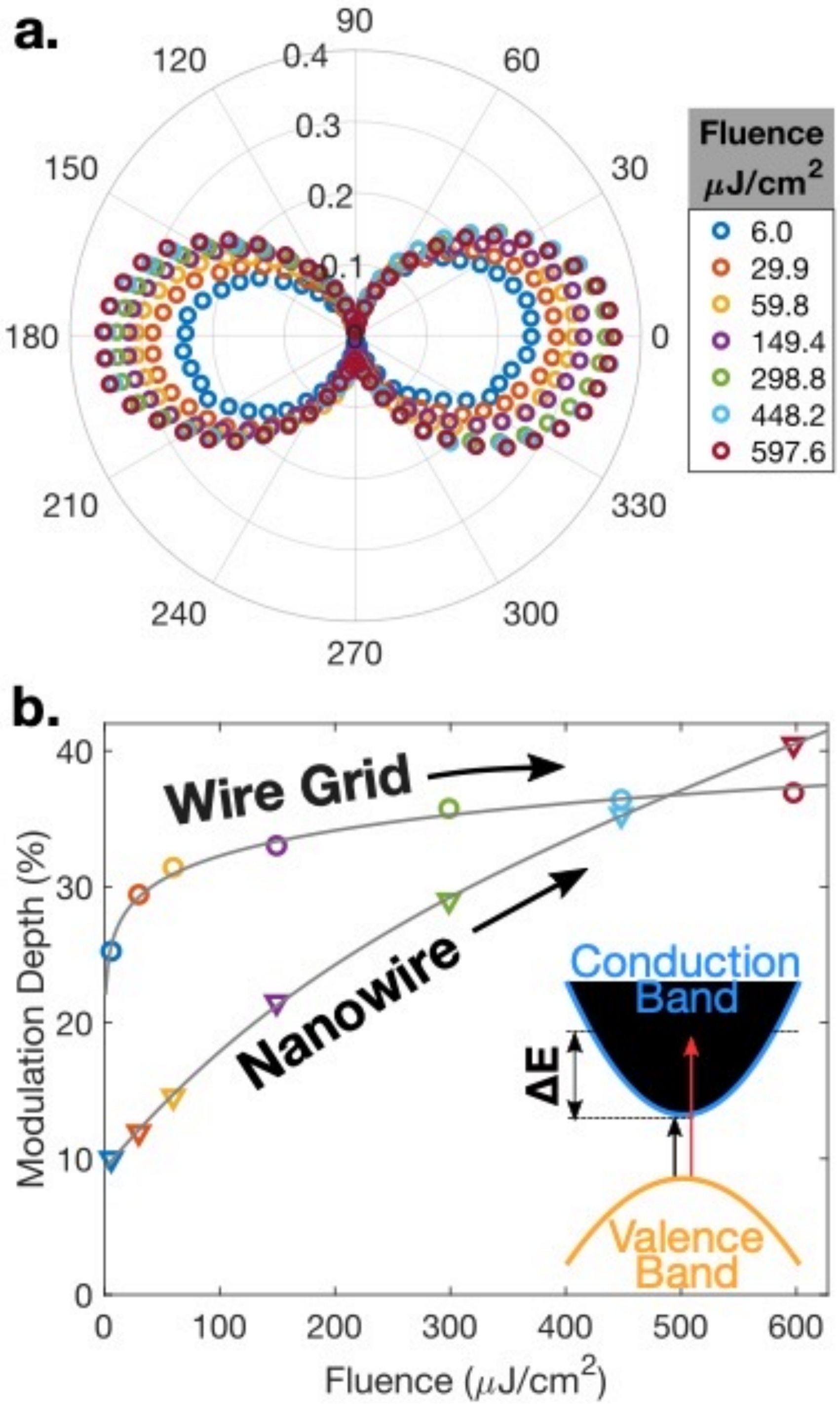
NCI
PROVIDING AUSTRALIAN RESEARCHERS WITH WORLD-CLASS HIGH-END COMPUTING SERVICES

UKRI Engineering and Physical Sciences Research Council

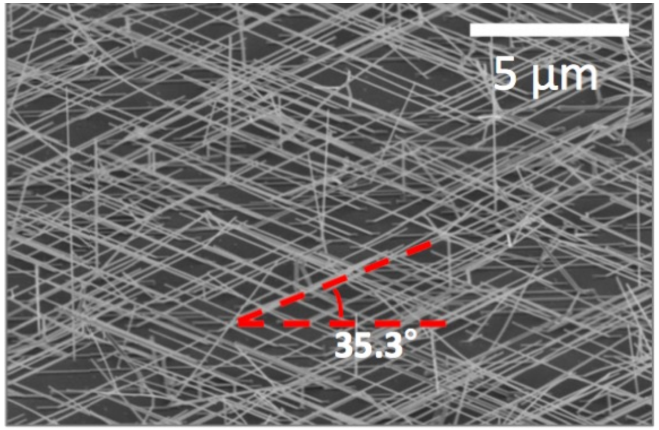
Australian Government
Australian Research Council

ANFF

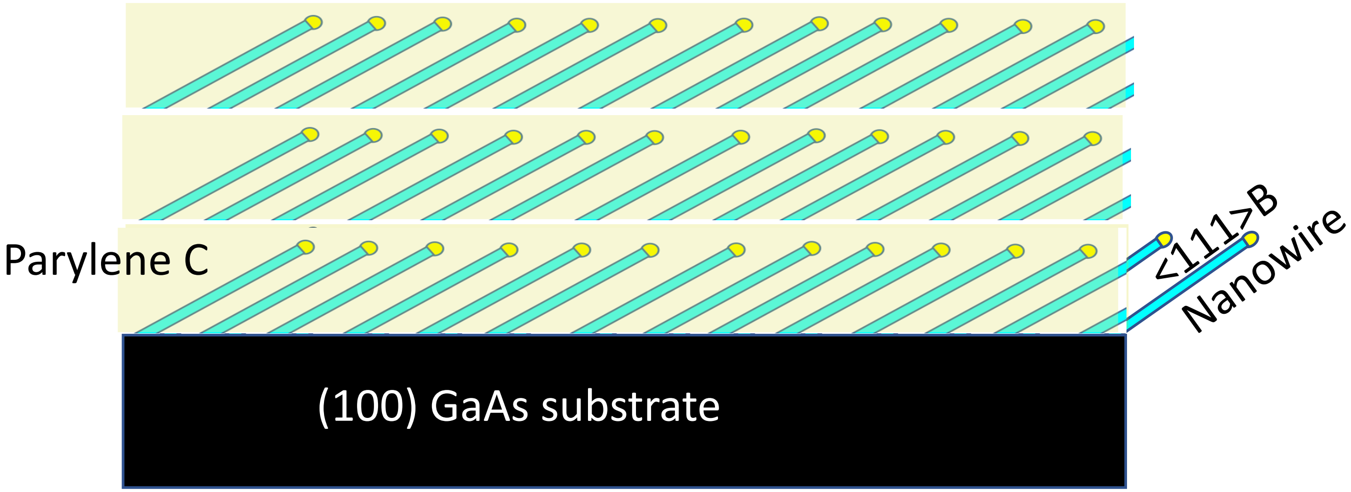


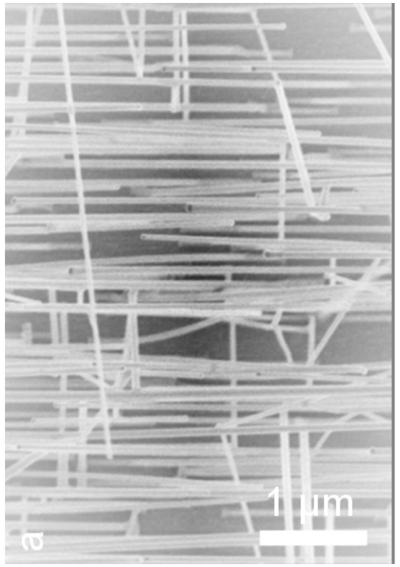

a.
90
60
30
0
330
300
270
240
210
180
150
120
0.4
0.3
0.2
0.1
Fluence
μJ/cm^2
6.0
29.9
59.8
149.4
298.8
448.2
597.6
b.
Wire Grid
Nanowire
Conduction Band
Valence Band
ΔE
Modulation Depth (%)
Fluence (μJ/cm^2)
0
10
20
30
40
0
100
200
300
400
500
600

Nanowire-Based THz Modulator – Fabrication

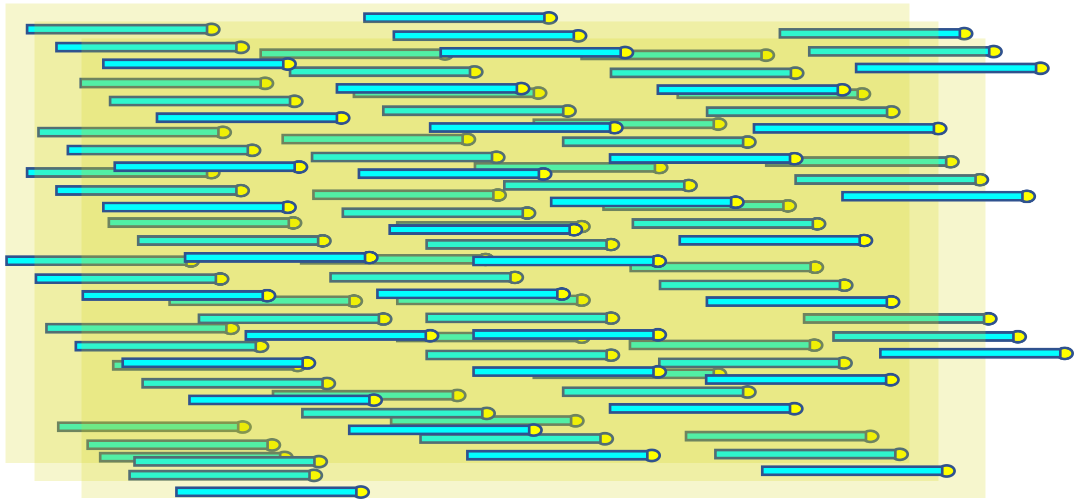


EDGE VIEW

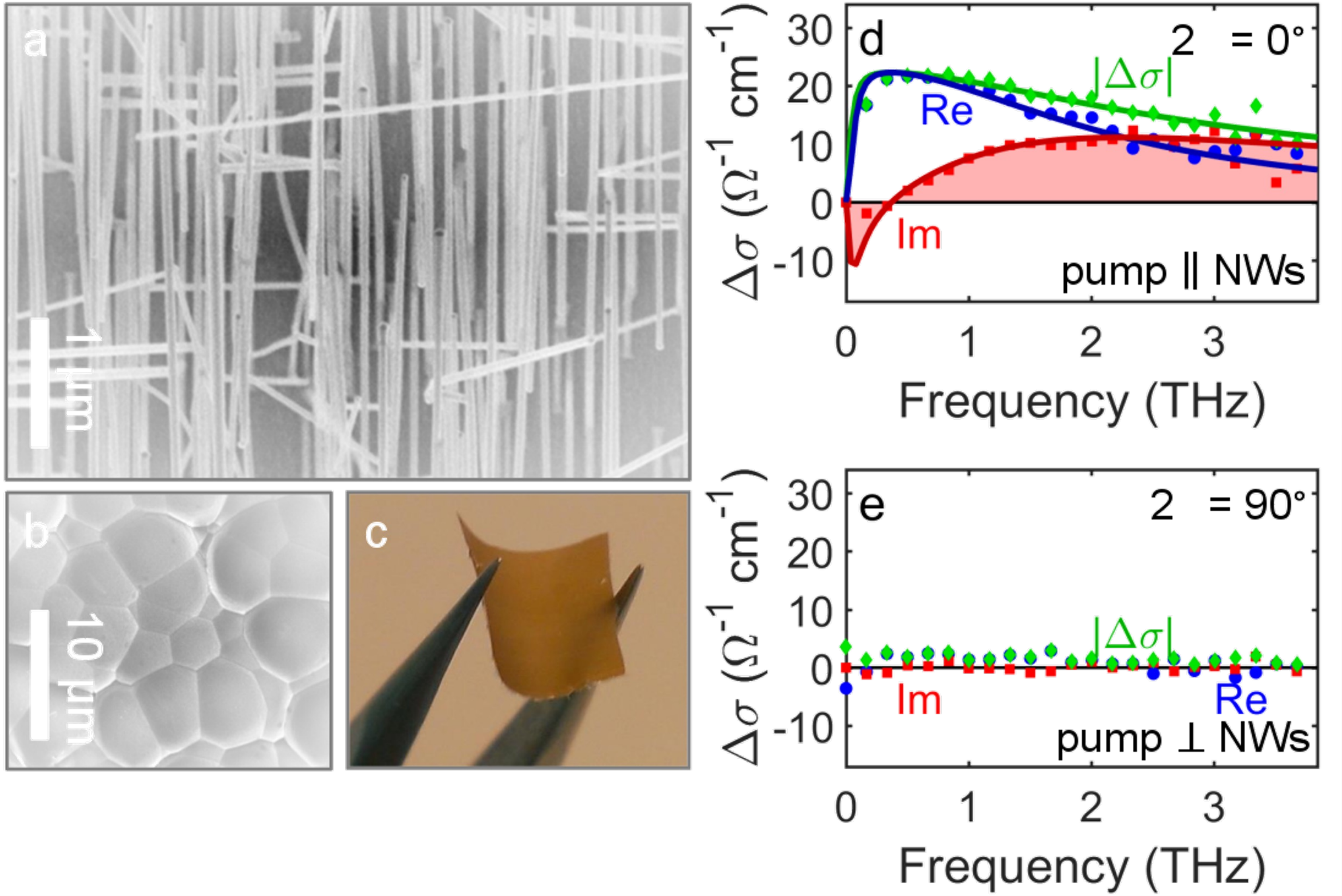




TOP VIEW



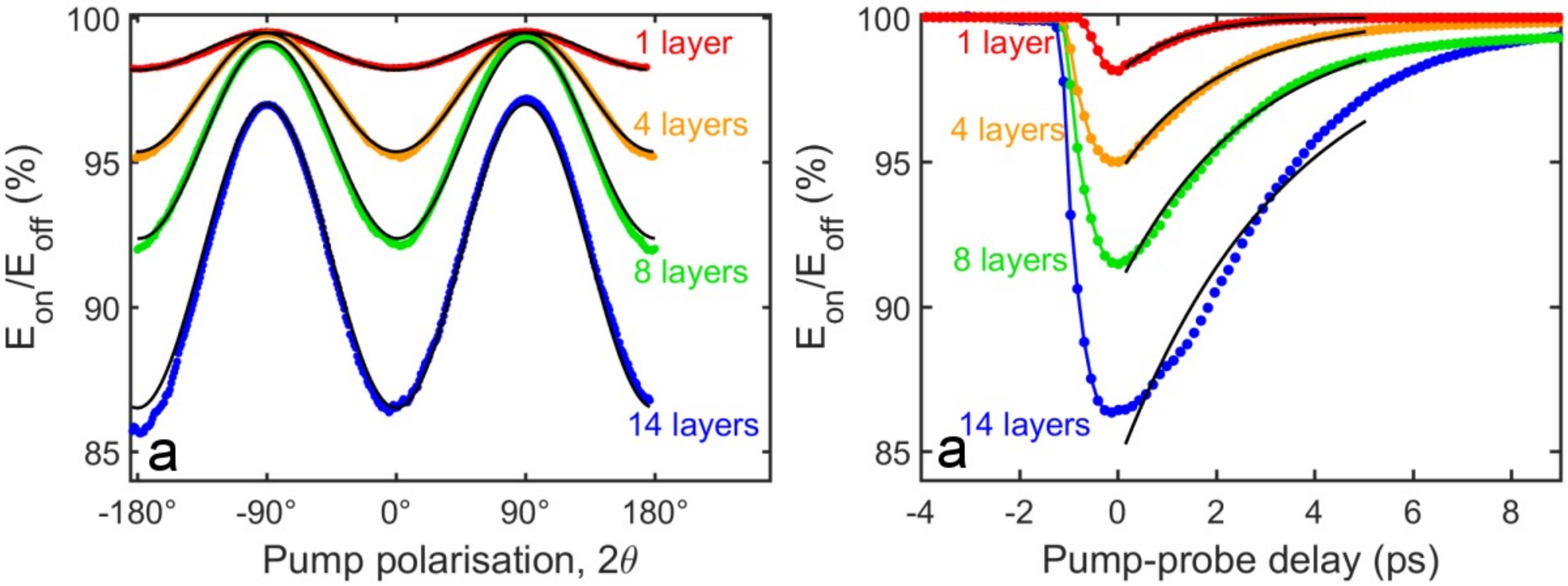
Nanowire-Based THz Modulator – Fabrication



For desription of AC conductivity spectrum see MB2.5 and Boland *Nanoscale,* 9, 7839–7846 (2017)

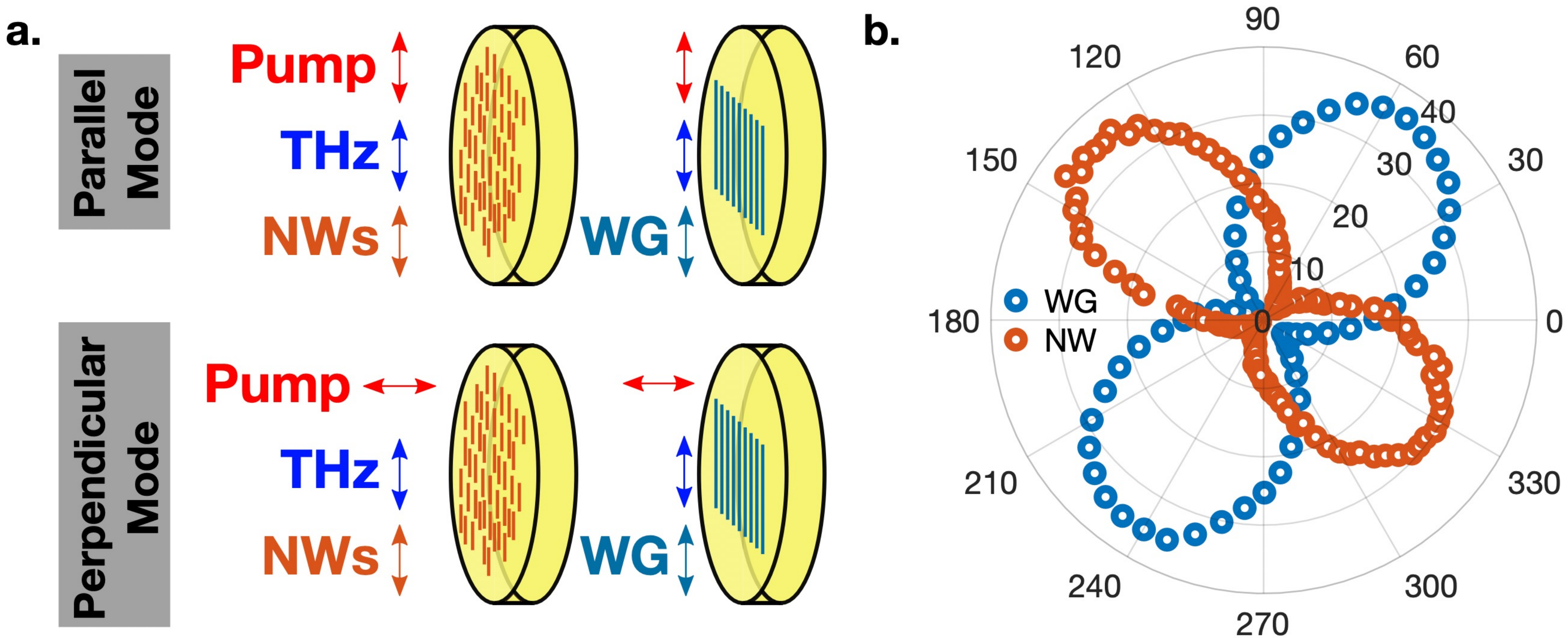
Baig et al. *Nano Lett.* 17:2603 (2017)

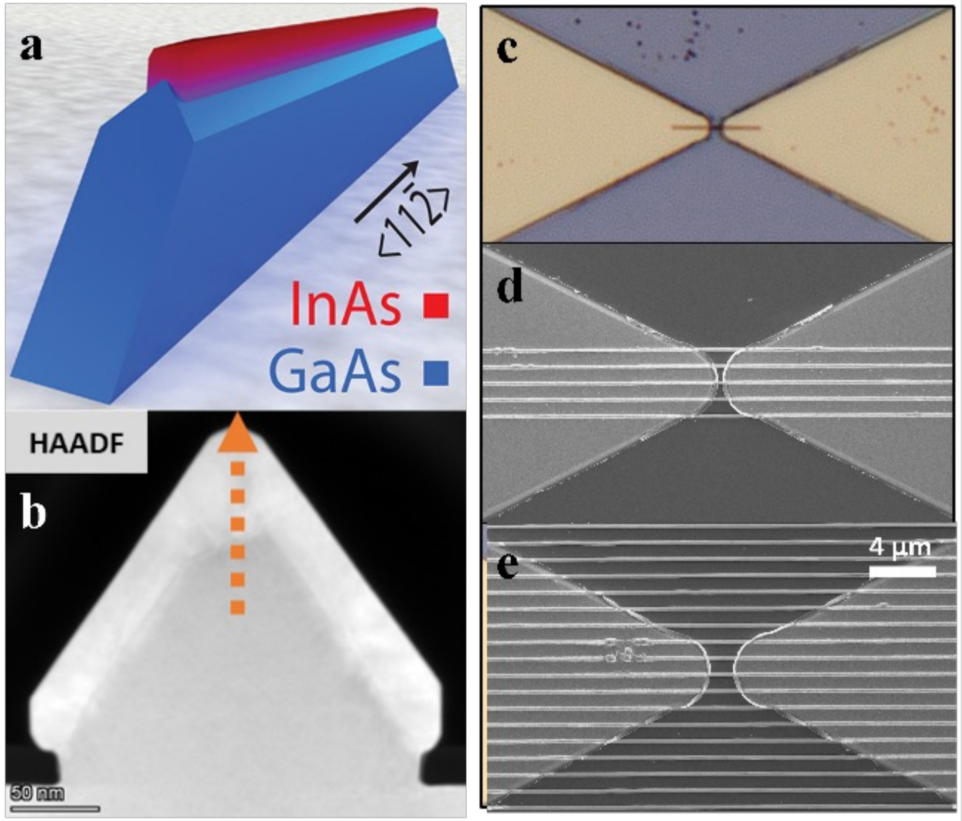
Nanowire-Based THz Modulator – Testing

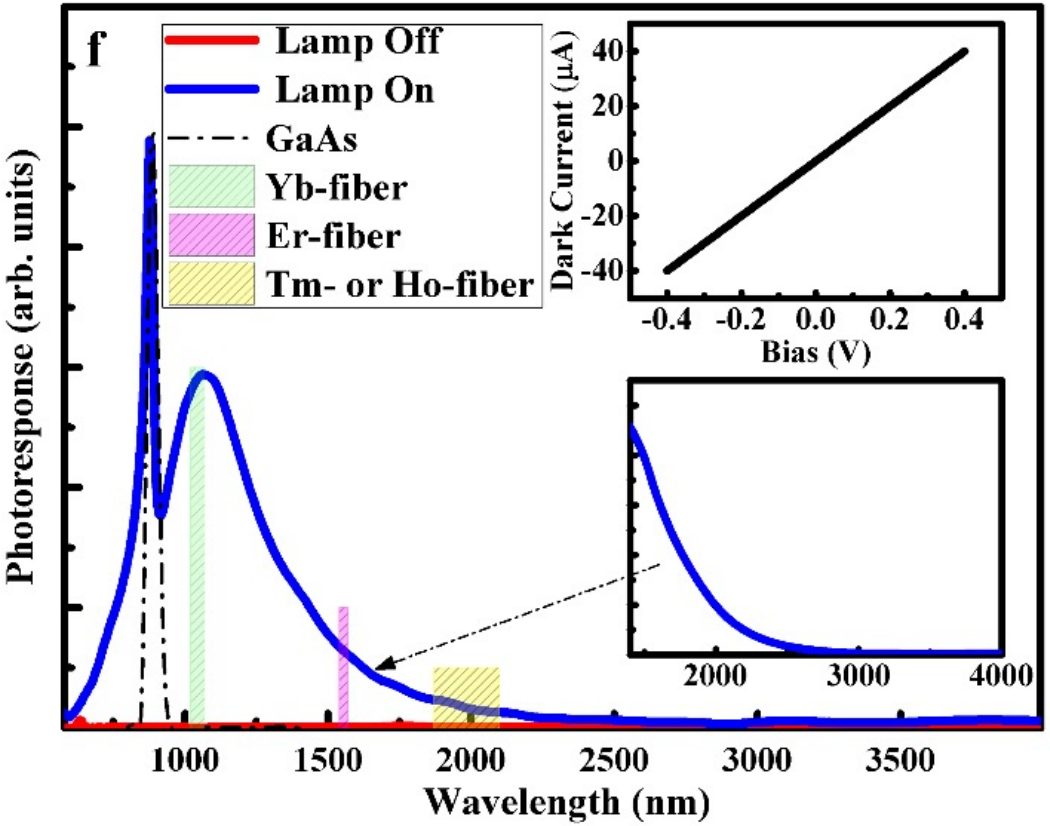


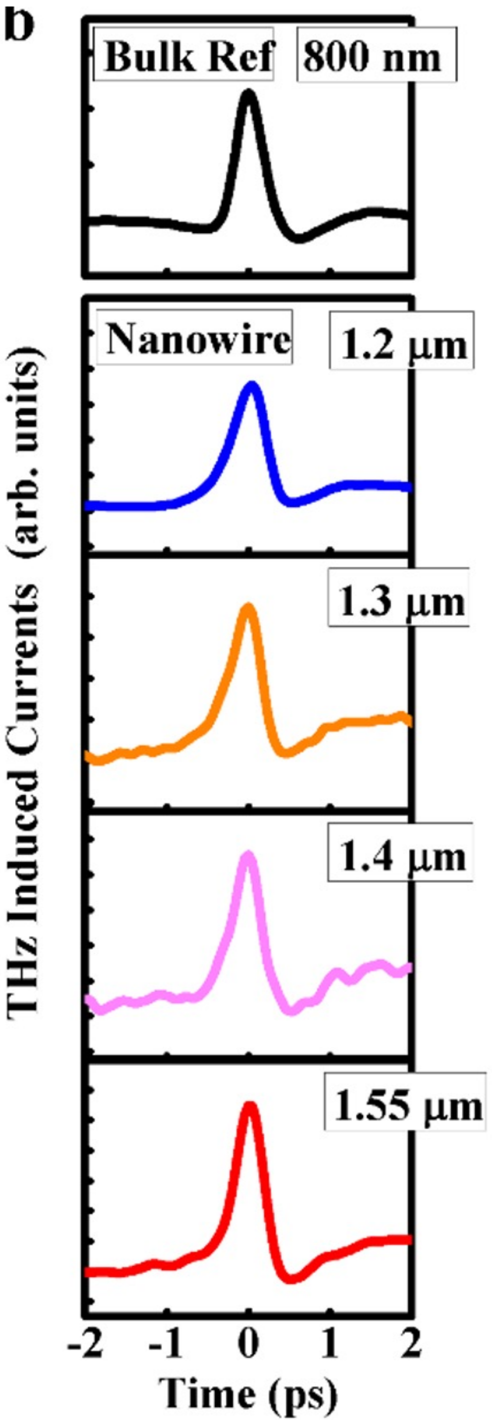
- Extinction ratio and modulation depth increases with number of layers.
- Carrier lifetimes also seems to increase with no of layers but still picosecond lifetime so allows for picosecond switching speeds.

Baig et al. *Nano Lett.* 17:2603 (2017)


a.
Parallel Mode
Pump
THz
NWs
WG
Perpendicular Mode
Pump
THz
NWs
WG
b.
90
60
30
0
330
300
270
240
210
180
150
120
10
20
30
40
0
WG
NW


a
<112>
InAs
GaAs
HAADF
b
50 nm
c
d
e
4 µm


f
Lamp Off
Lamp On
GaAs
Yb-fiber
Er-fiber
Tm- or Ho-fiber
Photoresponse (arb. units)
Wavelength (nm)
1000
1500
2000
2500
3000
3500
Dark Current (µA)
Bias (V)
-0.4
-0.2
0.0
0.2
0.4
40
20
0
-20
-40
2000
3000
4000


b
Bulk Ref
800 nm
Nanowire
1.2 µm
1.3 µm
1.4 µm
1.55 µm
THz Induced Currents (arb. units)
Time (ps)
-2
-1
0
1
2