FEL-pumped Silicon lasers based on hydrogen-like impurity centers

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DLR

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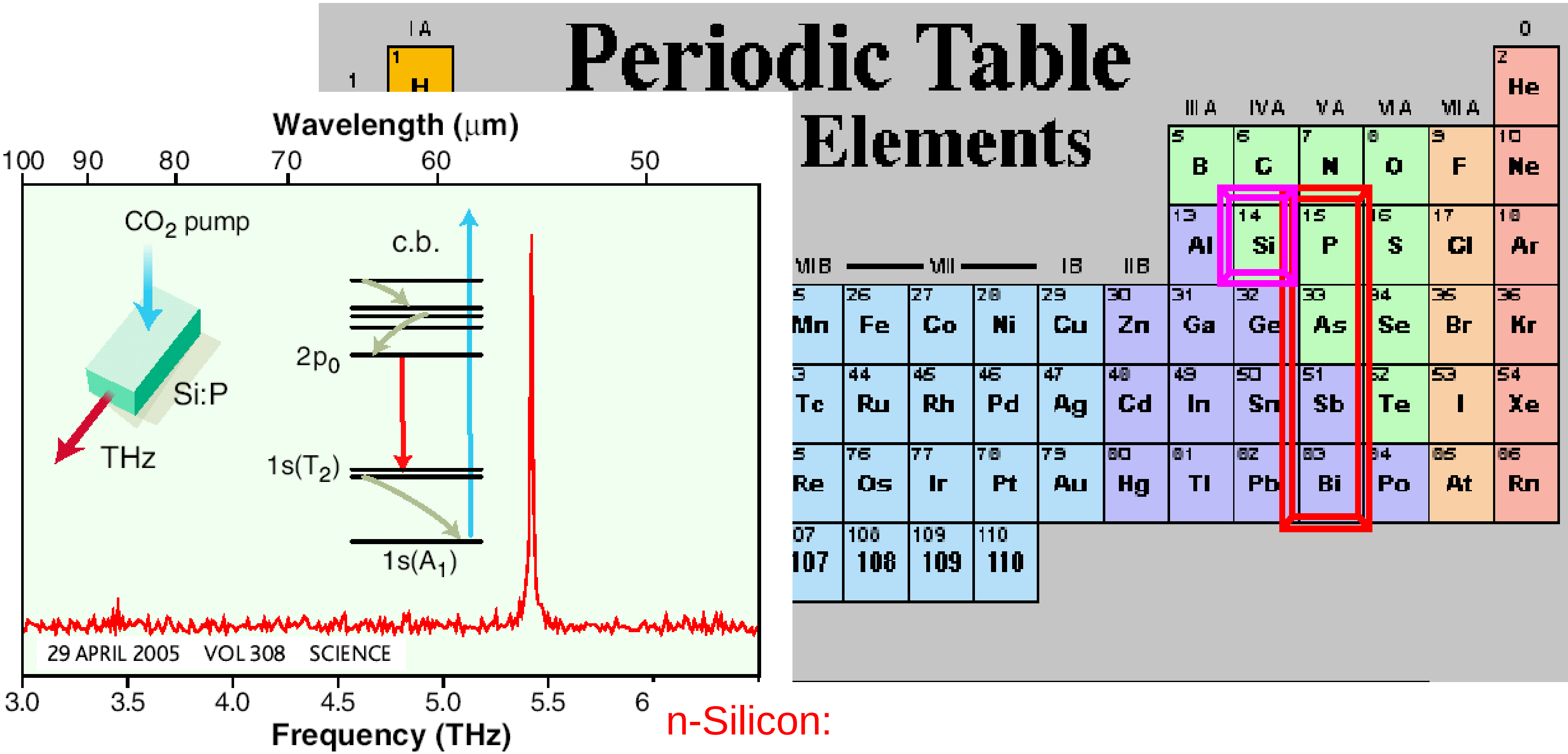
Outline

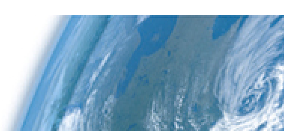
- Motivation
- Impurity states in Silicon
- n-type Silicon lasers
  - based on photoionization
  - based on photoexcitation
- THz Silicon Raman laser
- p-type Silicon laser
- Summary

Basic idea



n-Silicon:

- Hydrogen like energy levels of shallow impurities
- Transitions between states are in the THz range
- Make use of peculiarities of these levels:
  long-lived states, resonant phonon interaction



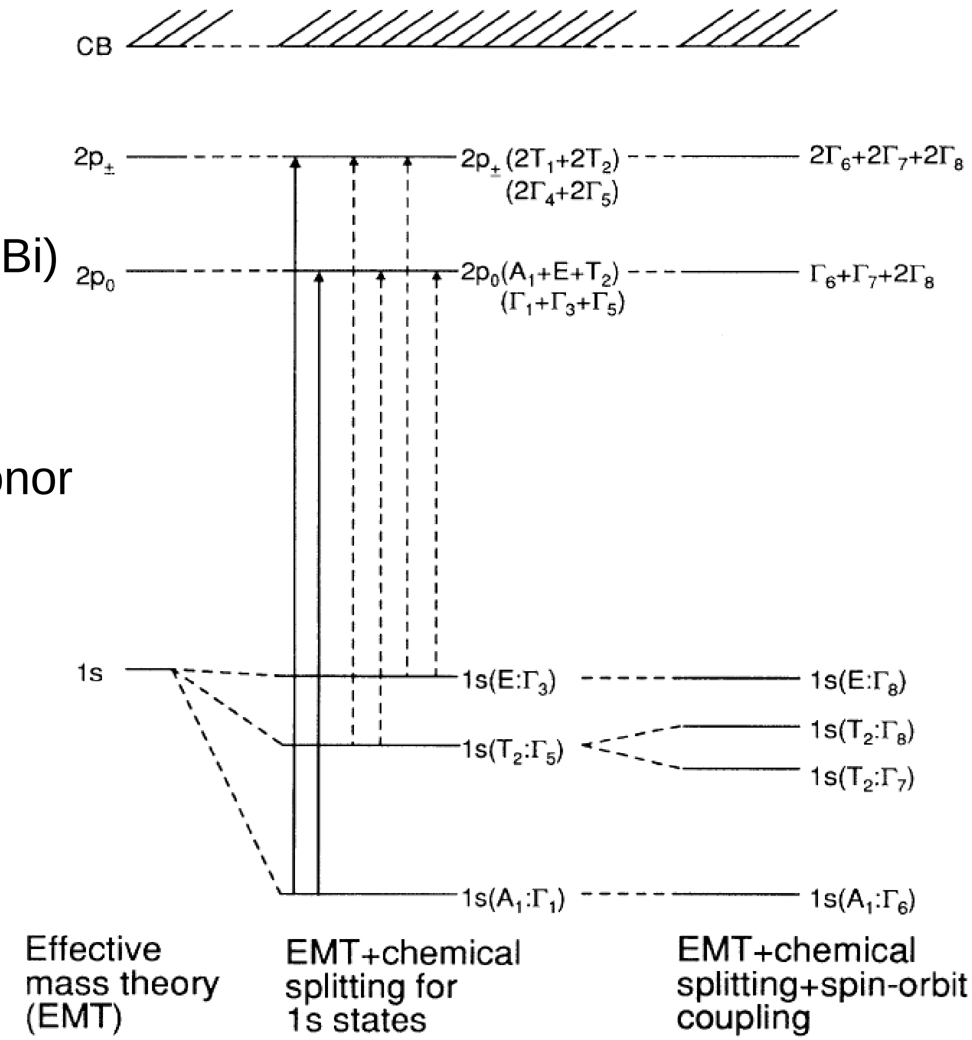
Impurity states in n-type Si

Doping with group-V donors

- Substitutional Donors (P, As, Sb, Bi)
- Hydrogen-like spectrum (EMT)

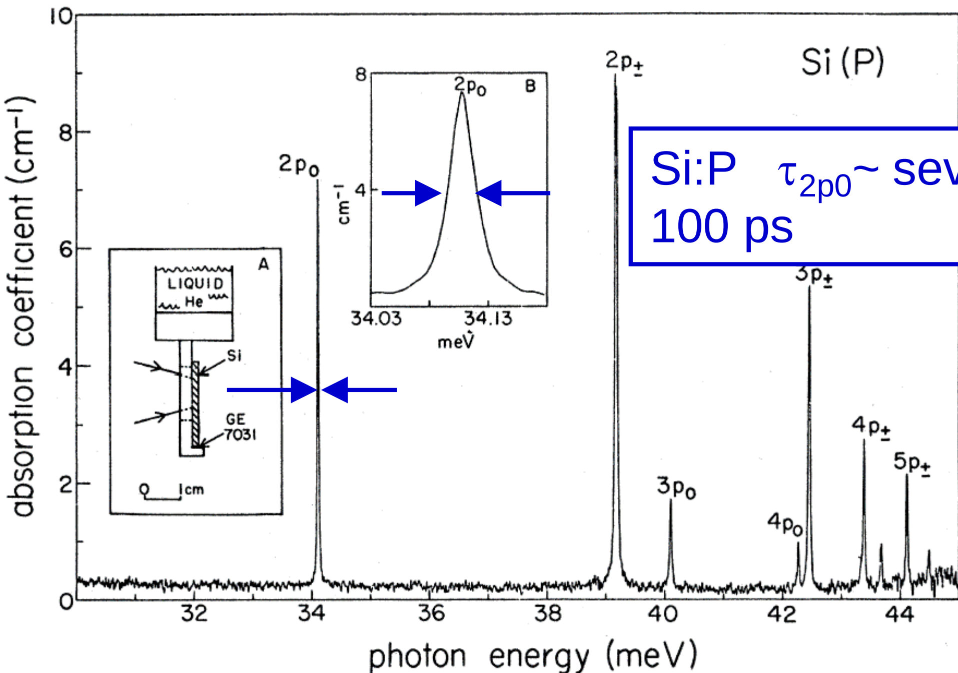
$$E_n = - R / n_2\ \varepsilon^2\ (m_D/m)$$

- Chemical splitting depends on donor
- Spin-orbit coupling

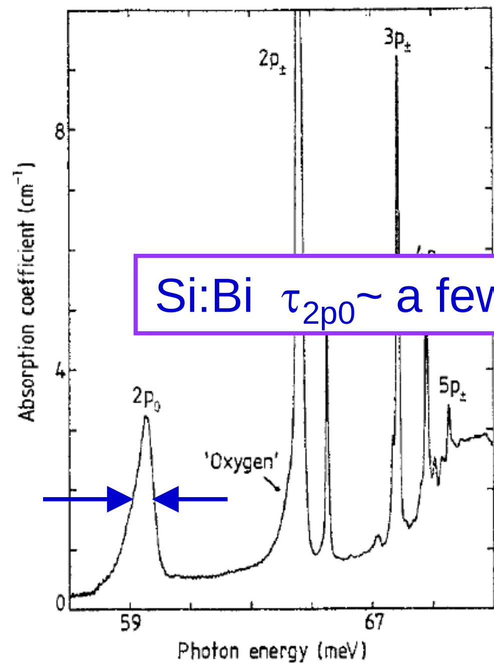


Mayur et al., PRB 1993

Spectroscopy and life times



Si:P τ_{2p0}~ several 100 ps



Si:Bi τ_{2p0}~ a few ps

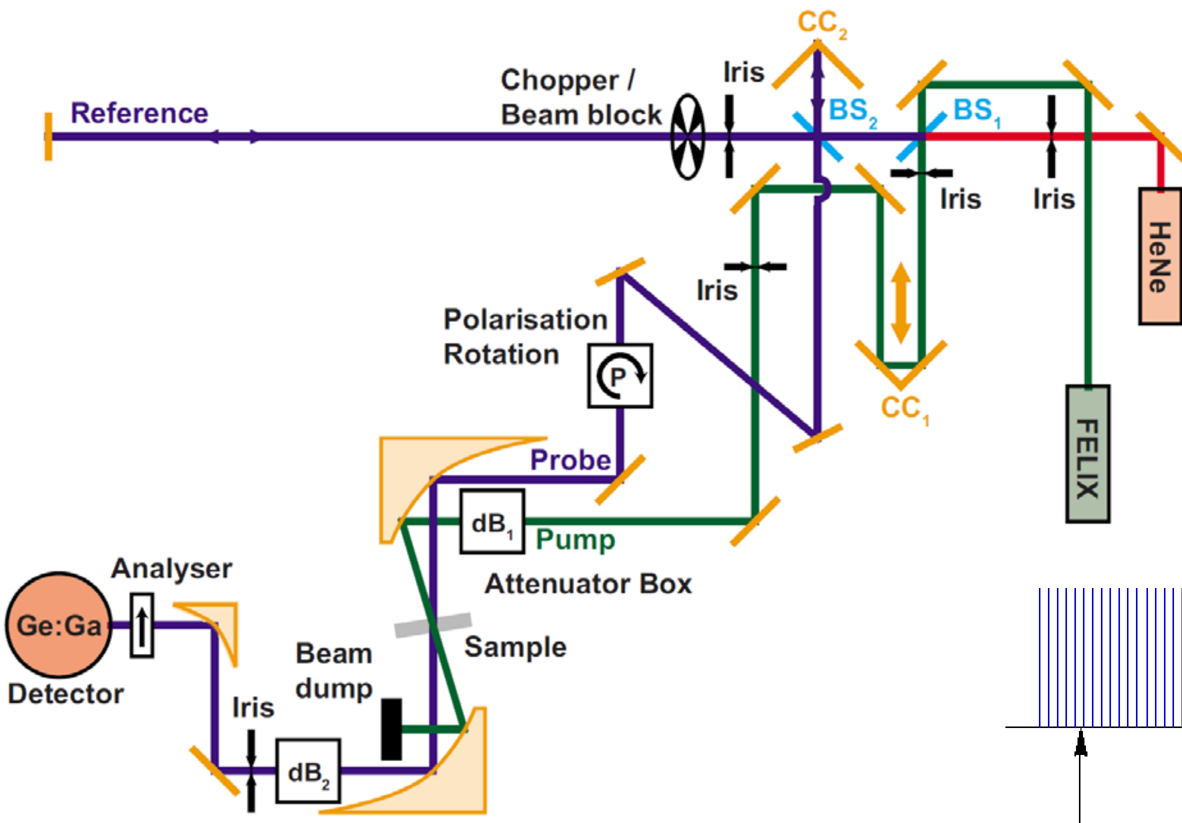
long life times of impurity states

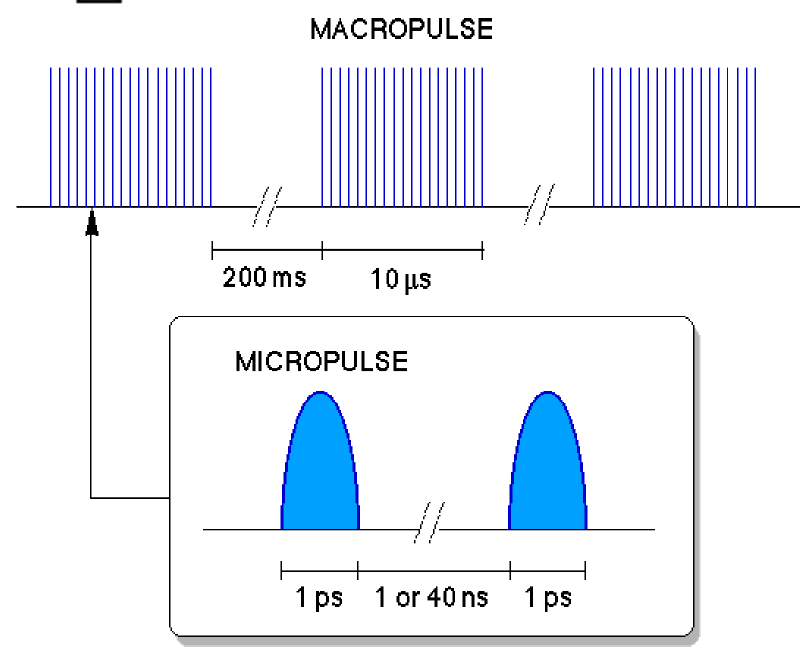
short life times of impurity states

Jagannath et al., PRB **23**, 2082 (1981)

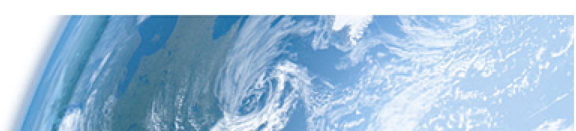
Butler et al., PRB **12**, 3200 (1975)

Pump-probe set-up at FELIX

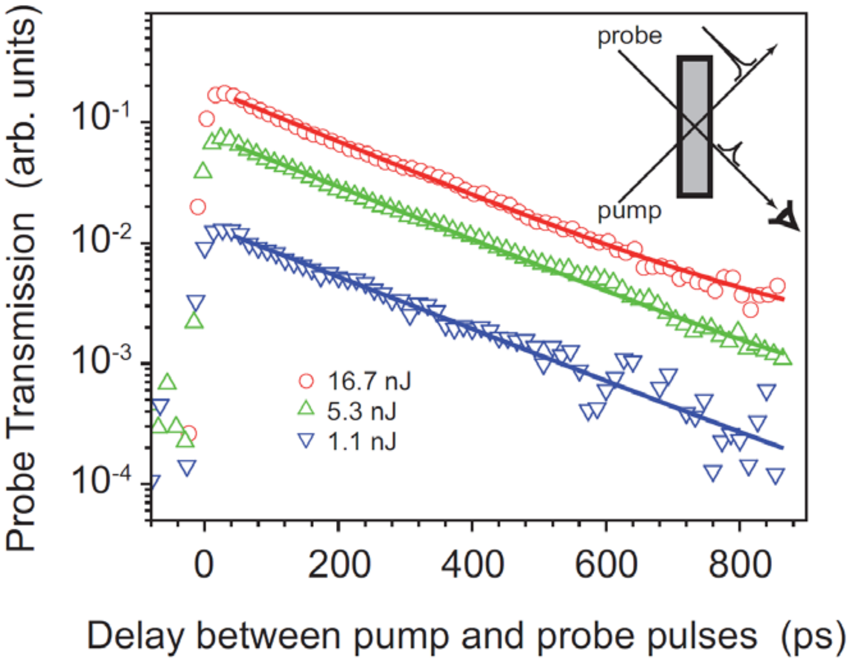


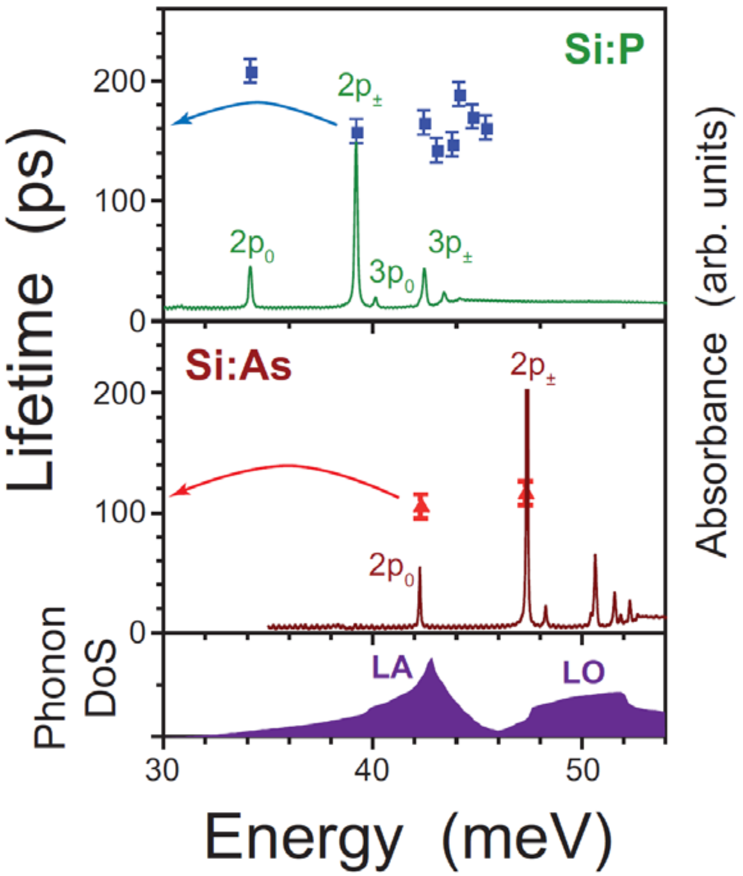


S. Lynch et al., PRB 82, 245206 (2010)



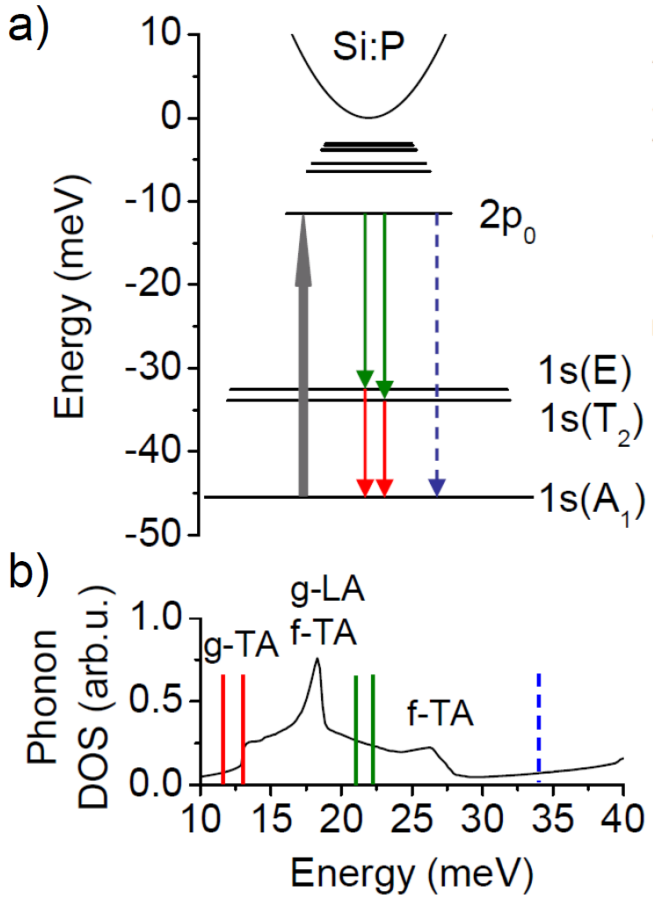
Lifetime measurements by pump-probe technique

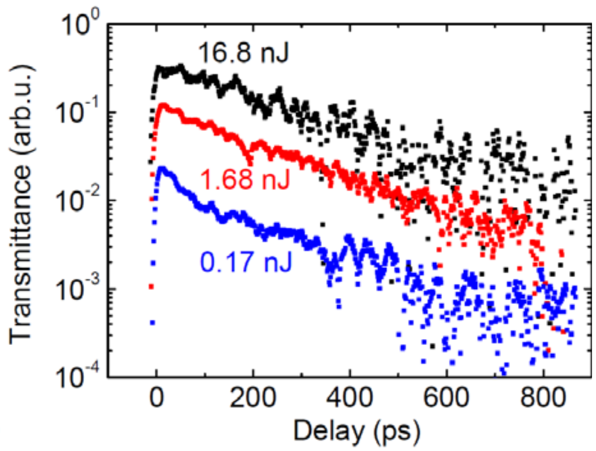


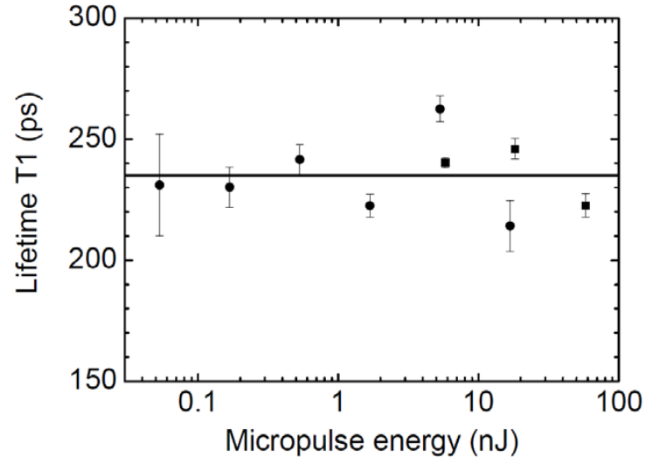


N. Vinh et al., PNAS 105, 10649 (2008)

Lifetime: natural Si:P vs. isotopically pure ^{28}Si







H.-W. Hübers et al., PRB (2013)

- ^{nat}Si: 92.23% ^{28}Si, 4.67% ^{29}Si, 3.1% ^{30}Si
- ^{28}Si: purity > 99.994, doping = 2×10^{15} cm^{-3}
- $T_1(^{28}Si)$ = 235 ps > $T_1(^{nat}Si)$ = 205 ps
- The longer lifetime of ^{28}Si is due to its higher symmetry and a less pronounced interaction of the $2p_0$,1s(E) and 1s(T_2) states with the g-LA and f-TA phonons.

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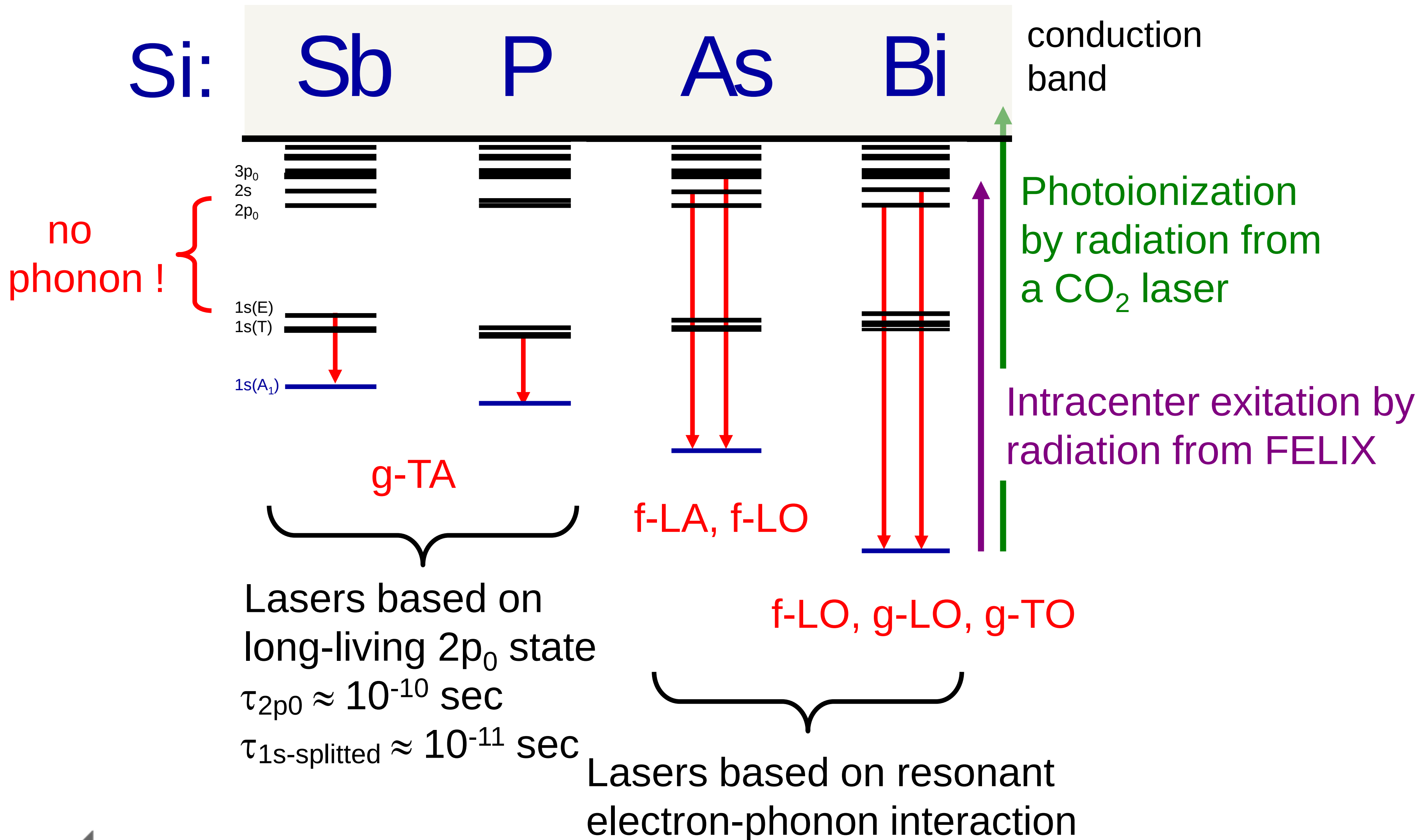
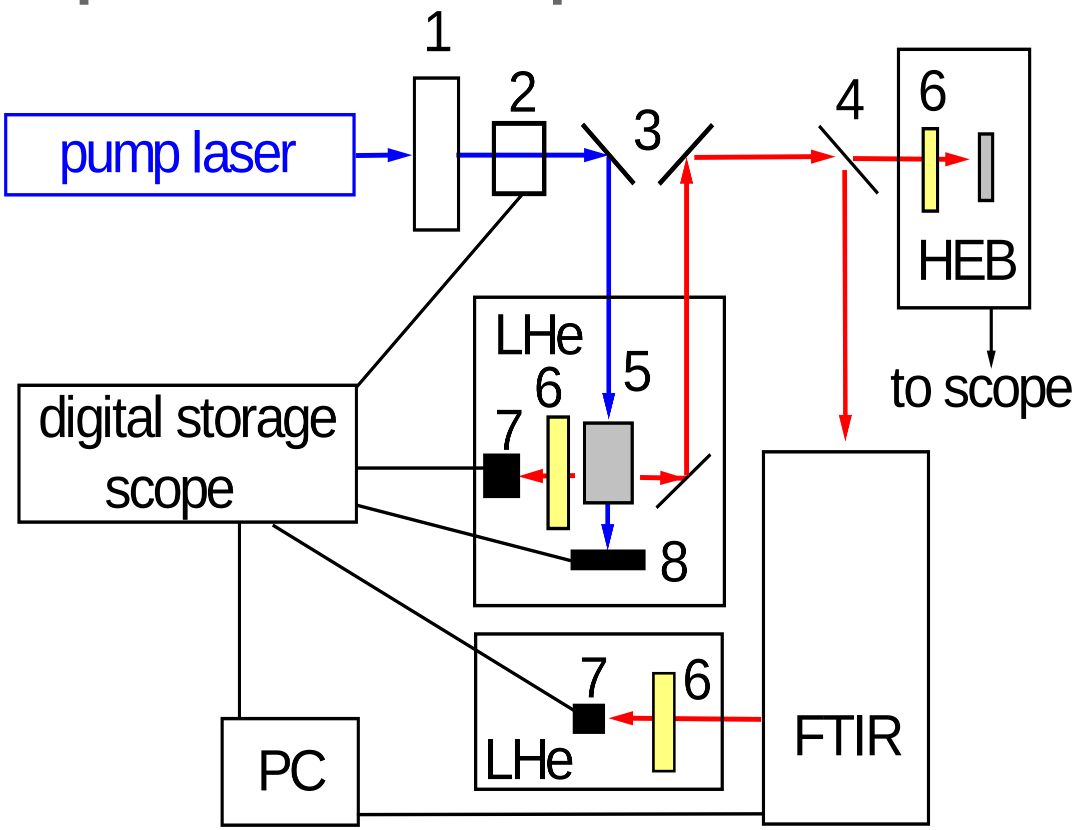
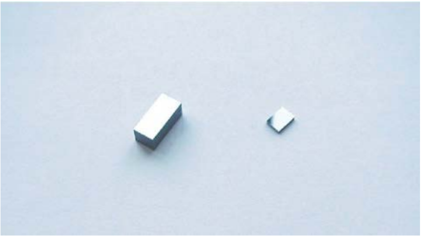
Interaction with phonons



Experimental setup

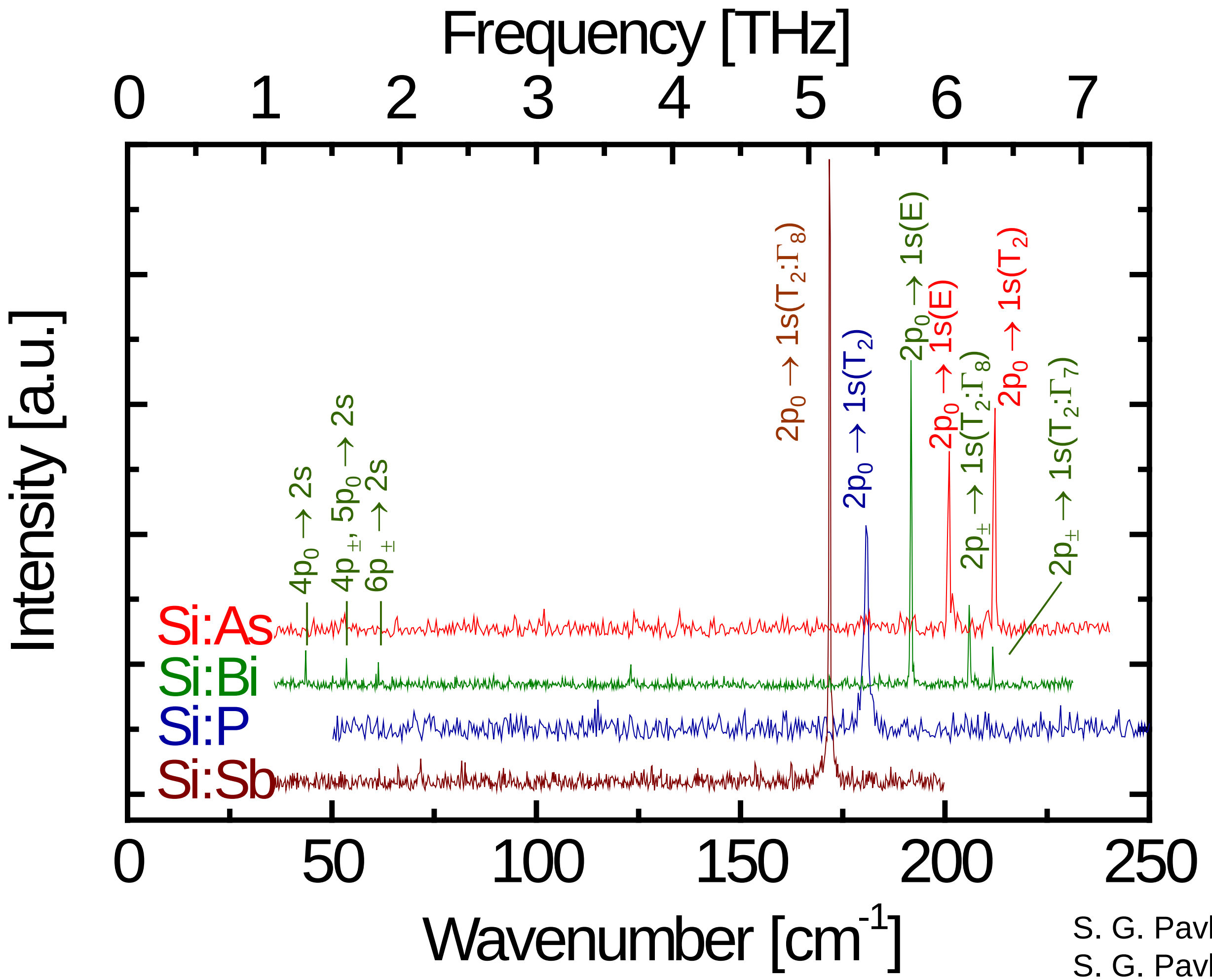


1 - pump attenuator
2 - photon drag monitor
3 - mirrors
4 - beam splitter
5 - sample
6 - FIR filters
7 - FIR detector
8 - alignment detector



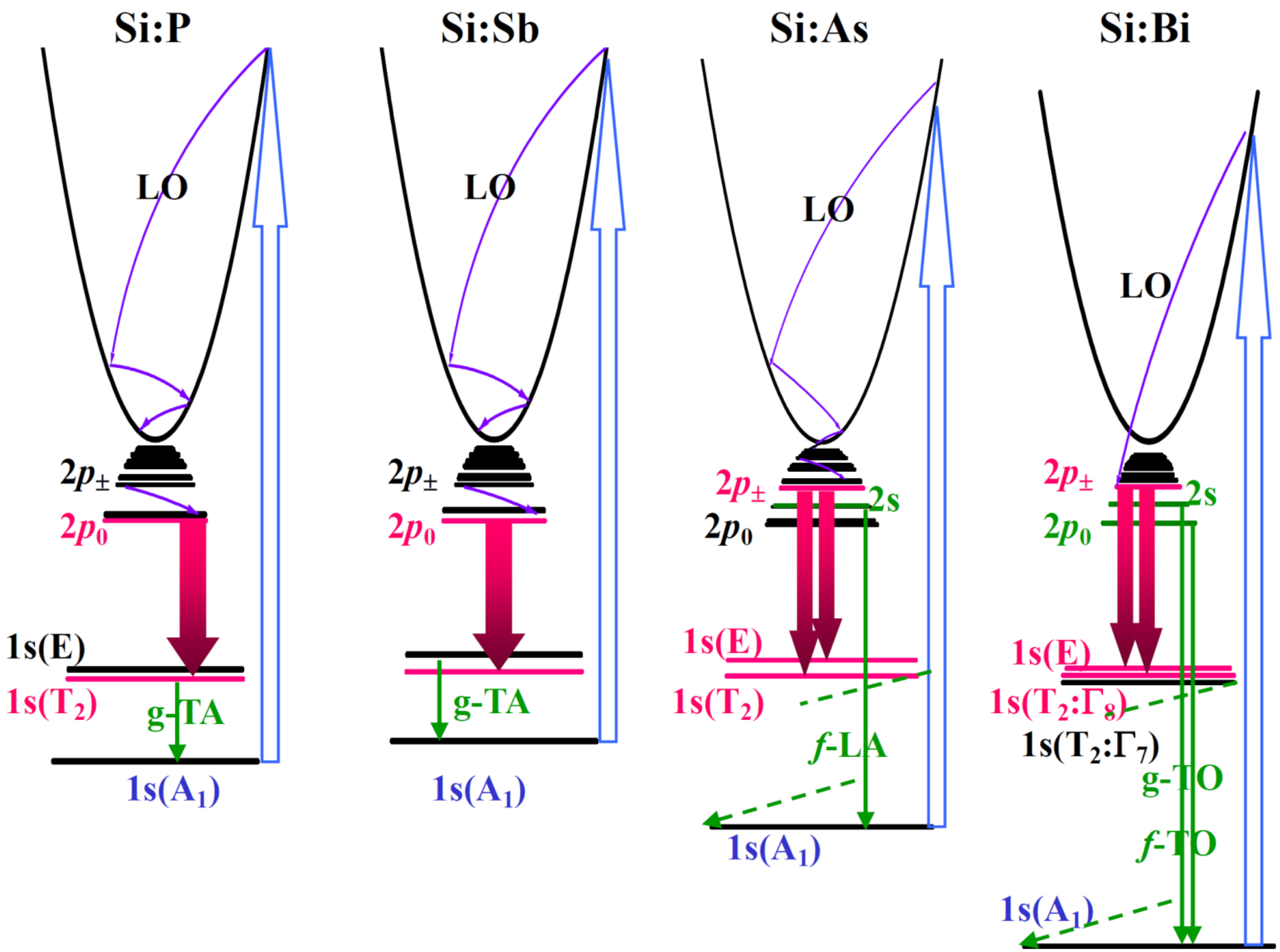
n-Si monocrystals
doped ~ 10^{15} - 10^{16} cm^{-3},
compensated < 30 %
length is 5-15 mm
FZ or CZ grown

Photoexcitation with a CO_2 laser: spectra



S. G. Pavlov et al., PRL **84**, 5220, 2000
S. G. Pavlov et al., APL **80**, 4717, 2002
S. G. Pavlov et al., JAP **92**, 5632, 2002
H.-W. Hübers et al., APL **84**, 3600, 2004

Laser schemes under photoexcitation with a CO_2 laser



Comparison with spectroscopy

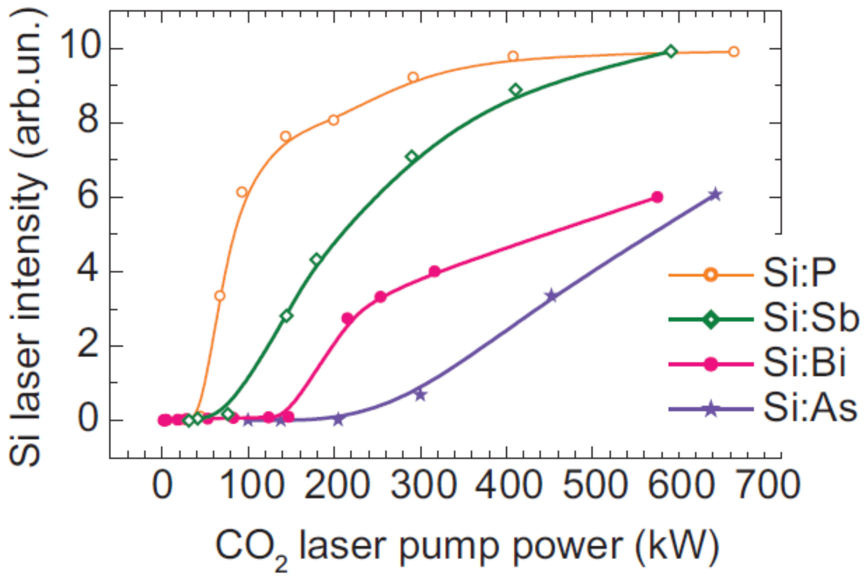
Table 1 Binding energy of some excited states for hydrogen-like donor centers in silicon as derived from an analysis of pump and emission spectra of silicon intracenter lasers under resonant photoexcitation.

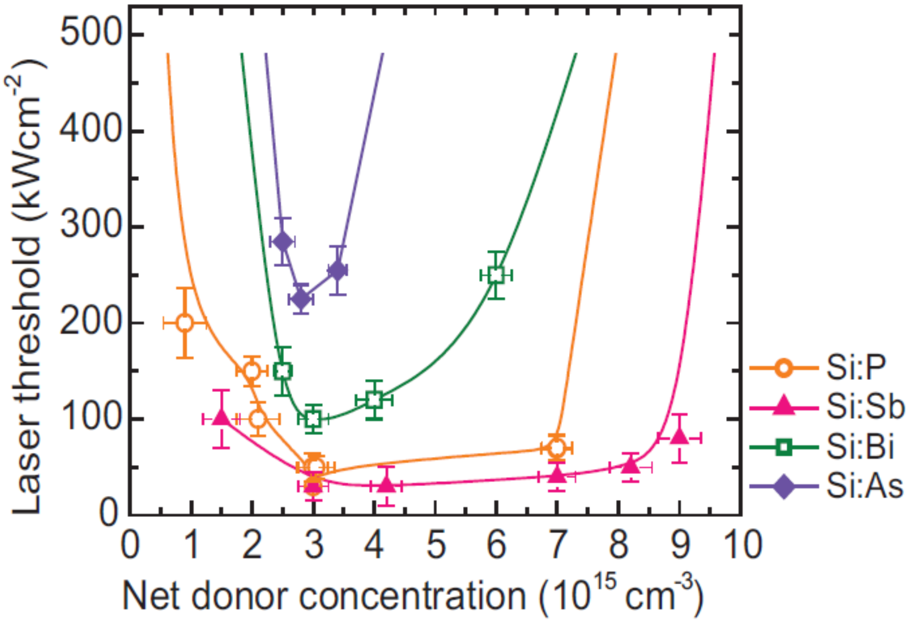
donor	$1s(T_2)$			$1s(E)$		
	n-Si lasing	cal.	spectroscopy	n-Si lasing	cal.	spectroscopy
P	33.91 ± 0.02 (4 K)	34.2	33.89 ± 0.01 (45 K)	32.61 ± 0.02 (4 K)	32.7	32.56 ± 0.01 (45 K)
Sb	32.83 ± 0.02^{a} (4 K)	32.9	32.83 ± 0.01^{a} (30 K)	30.50 ± 0.02 (4 K)	30.5	30.53 ± 0.01 (30 K)
			33.12 ± 0.01^{b} (30 K)			
As	32.73 ± 0.02 (4 K)	32.7	32.68 ± 0.01 (60 K)	31.34 ± 0.02 (4 K)	31.3	31.25 ± 0.01 (60 K)
Bi	31.90 ± 0.02^{a} (4 K)	31.3	31.89 ± 0.01 (80 K)	30.17 ± 0.02 (4 K)	31.3	30.47 ± 0.01 (80 K)
	32.63 ± 0.01^{b} (4 K)		32.89 ± 0.01^{HD} (10 K)			

[a]Doublet $1s(T_2{:}\Gamma_8)$; [b]singlet $1s(T_2{:}\Gamma_7)$. References: n-Si lasing: as deduced from pump and emission spectra of silicon intracenter lasers [24]; spectroscopy: impurity absorption spectroscopy at elevated crystal temperatures [92]; and for highly doped Si:Bi^{HD} at $T \sim 10$ K [93]; cal.: as calculated by EMT with an empiric model Hamiltonian [90]; for Si:Bi: from the standard EMT [38].

- Laser emission frequencies (measured at 4 K) and transition frequencies as measured by FTIR (measured at 30-80 K) agree very well.

Laser threshold

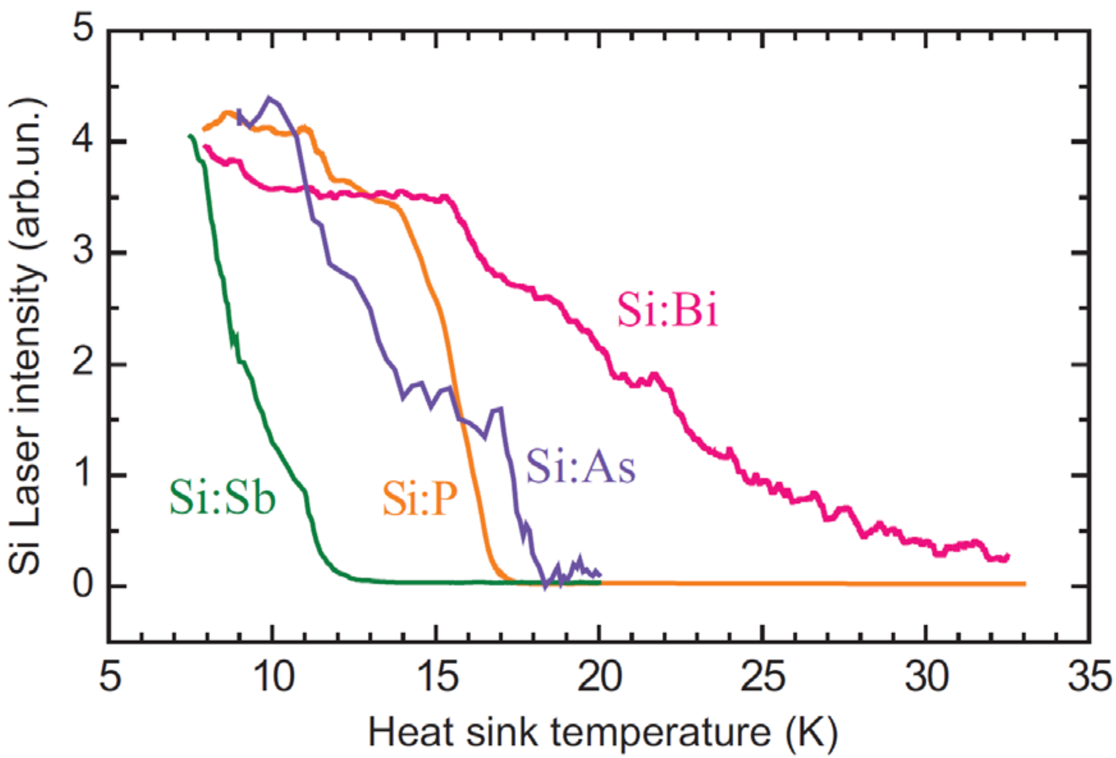




- Si samples at optimum doping concentration (3×10^{15} cm^{-3})
- Pumping at 10.59 µm, 100 kW/cm^2 = 5×10^{24} photons $cm^{-2}s^{-1}$
- Si:P, Si:Sb: $2p_0 \rightarrow 1s(T_2)$
- Si:As, Si:Bi: $2p_{\pm} \rightarrow 1s(E)$, $1s(T_2)$

- Si:P, Si:Sb: $2p_0 \rightarrow 1s(T_2)$, pumping at 10.59 µm, 400 kW/cm^2
- Si:As, Si:Bi: $2p_{\pm} \rightarrow 1s(E)$, $1s(T_2)$, pumping at 9.6 µm, 80 kW/cm^2
- Upper limit: impurity broadening, lifetime decreases
- Lower limit: too few donors, less gain

Temperature



- The larger the gap between the 1s(A) ground state and the 1s(E), 1s(T_2) split-off states the higher the operation temperature of the laser (less thermal population of the lower laser level).

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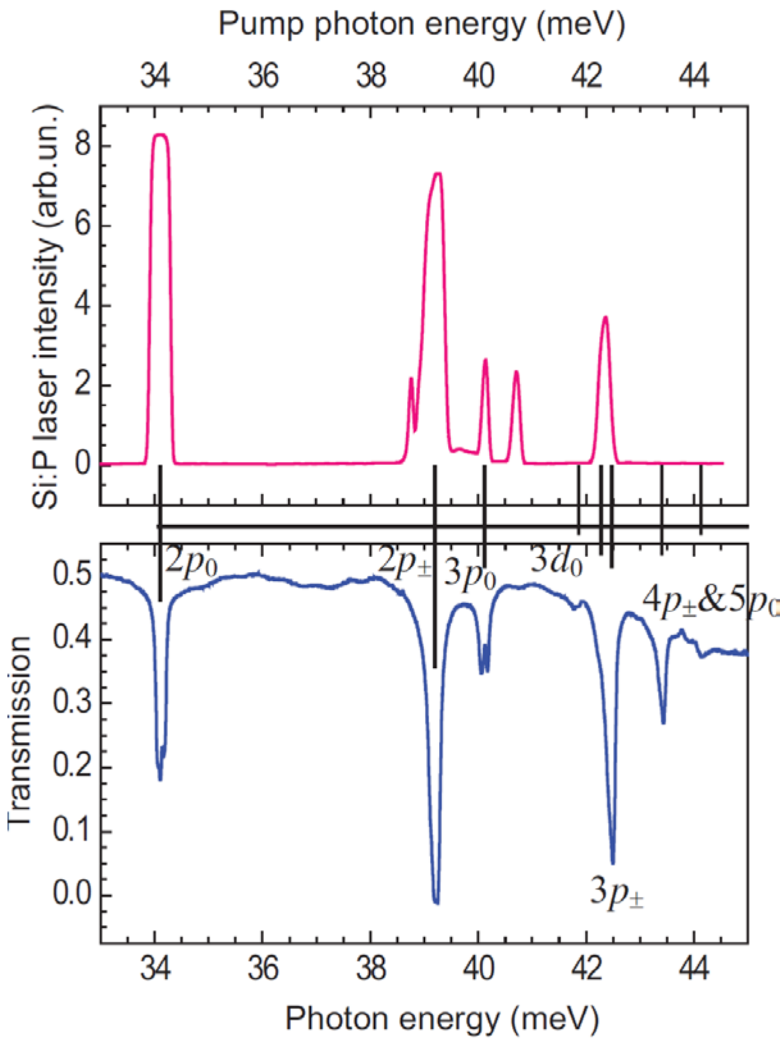
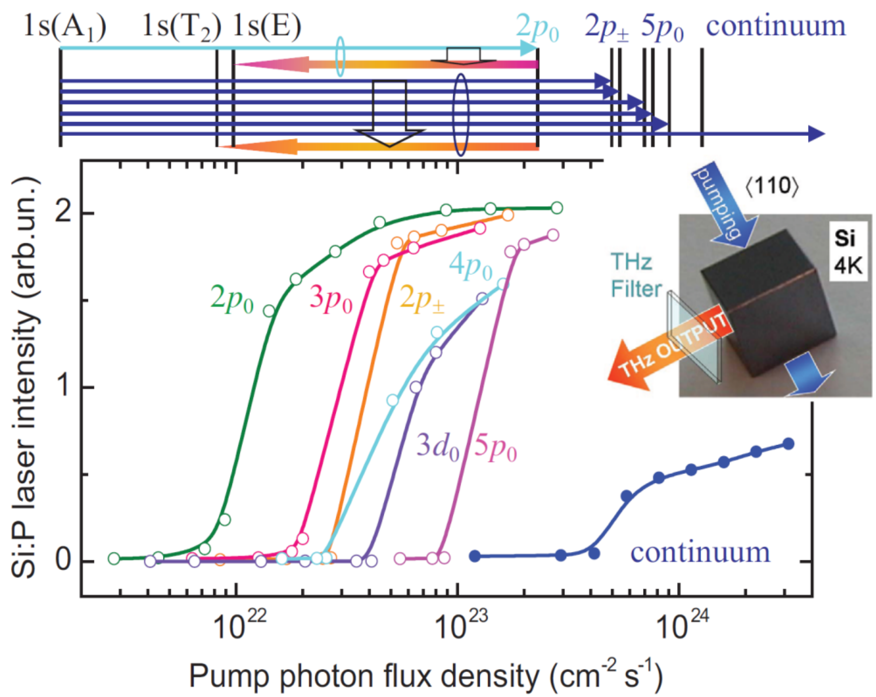
Photoexcitation of Si:P

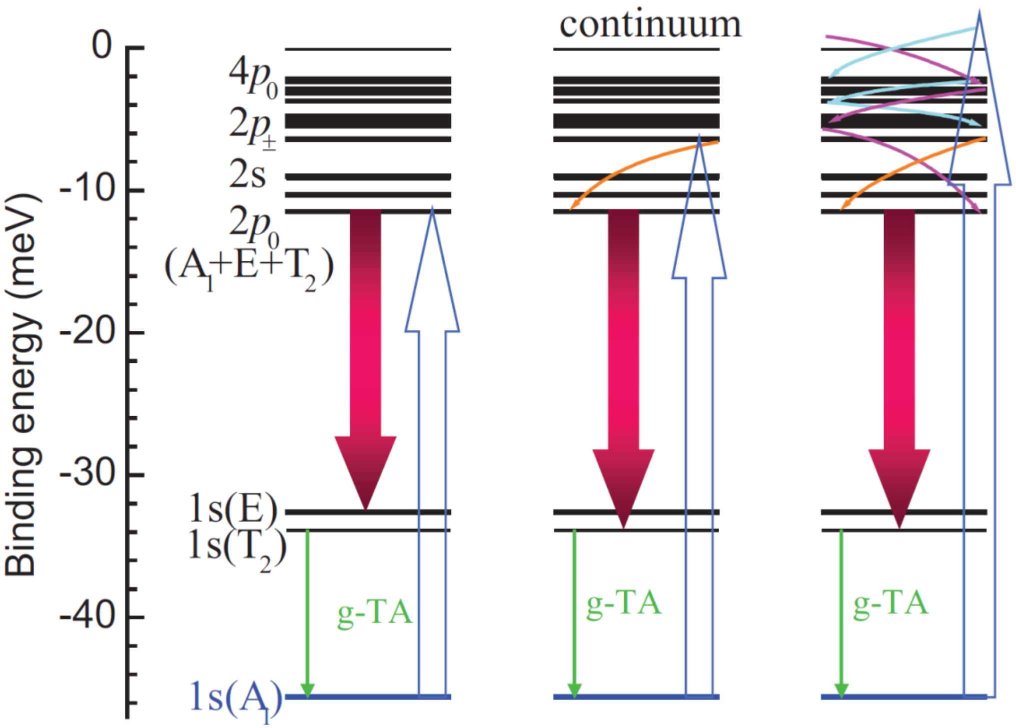




- At low pump power: laser emission only when pumped into a state
- The higher the pumped state the lower the laser threshold, due to increased non-radiative recombination

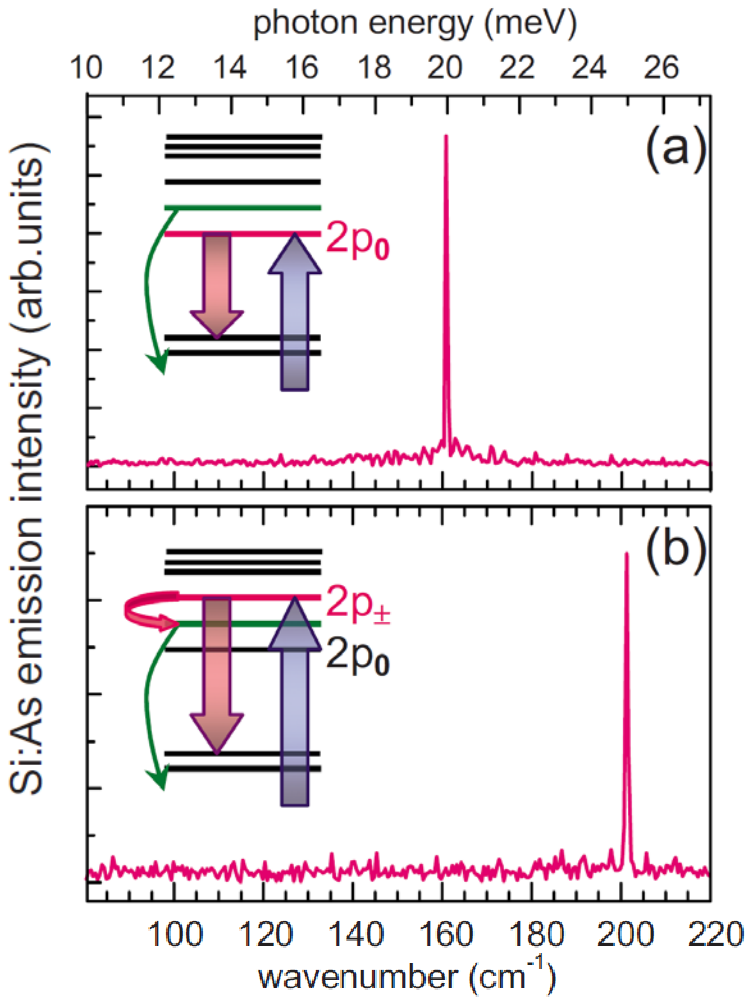
Photoexcitation of Si:P

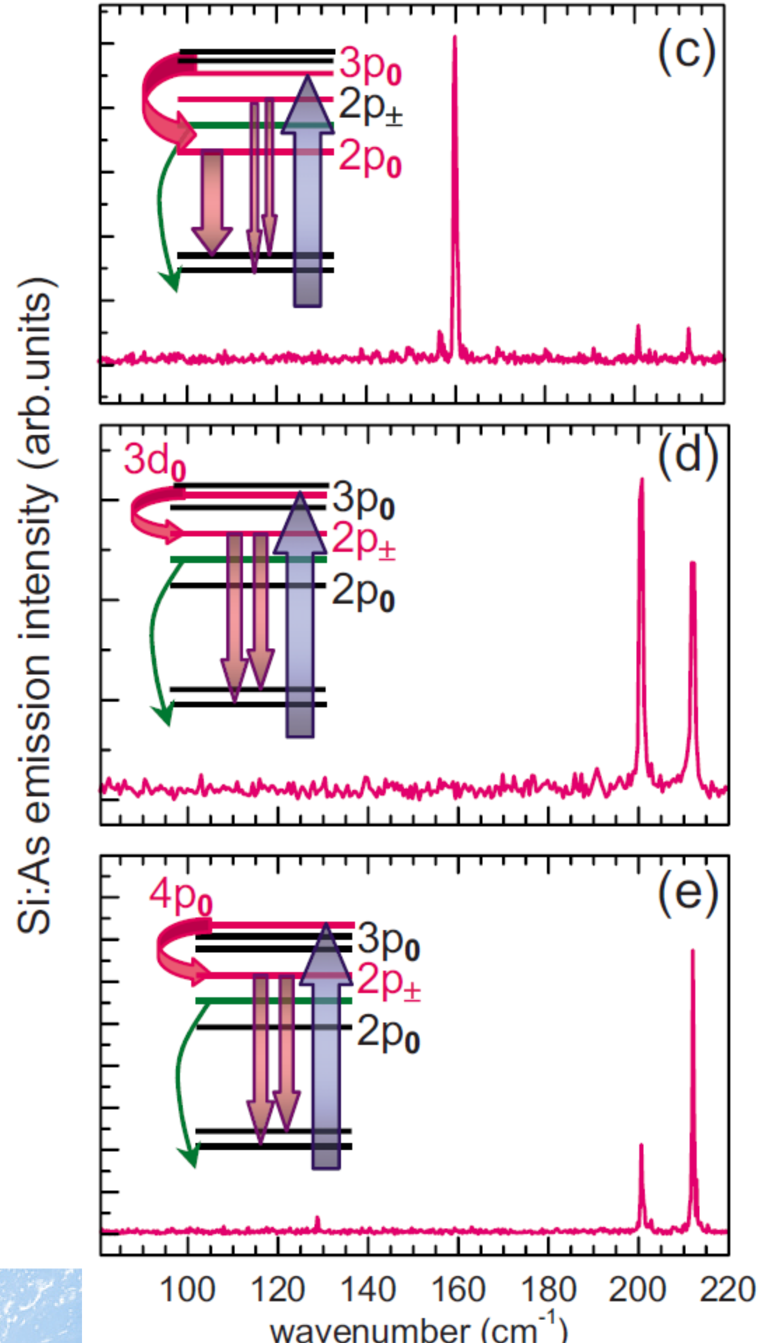
- Pumping into $2p_0$:
  $2p_0 \rightarrow 1s(E)$
- Pumping into a state > $2p_0$:
  $2p_0 \rightarrow 1s(T_2)$
- Pumping into conduction band:
  $2p_0 \rightarrow 1s(T_2)$



R. Kh. Zhukavin et al., Appl. Phys. B 76, 613 (2003)

Photoexcitation of Si:As



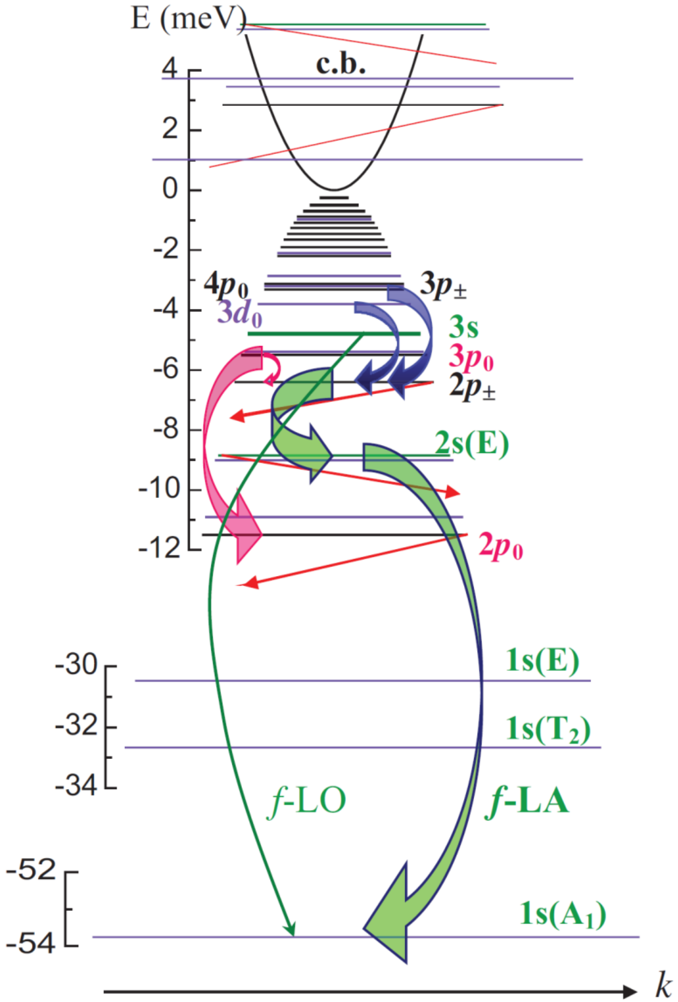


PRB **78**, 165201 (2008)

Photoexciation of Si:As

Pumping in

- $2p_0$: $2p_0 \rightarrow 1s(E)$
- $2p_\pm$: $2p_\pm \rightarrow 1s(T_2)$
- $3p_0$: $2p_0 \rightarrow 1s(E)$,
  $2p_\pm \rightarrow 1s(T_2)$,
  $2p_\pm \rightarrow 1s(E)$
- $3d_0$: $2p_\pm \rightarrow 1s(E)$,
  $2p_\pm \rightarrow 1s(T_2)$
- $4p_0$: $2p_\pm \rightarrow 1s(E)$,
  $2p_\pm \rightarrow 1s(T_2)$,
  $3d_0 \rightarrow 1s(E)$,
  $4p_0 \rightarrow 1s(T_2)$



The changes of the laser scheme with changing pump transition indicate that specific relaxation paths exist that are not described by a step-like relaxation from one to the next lower state.

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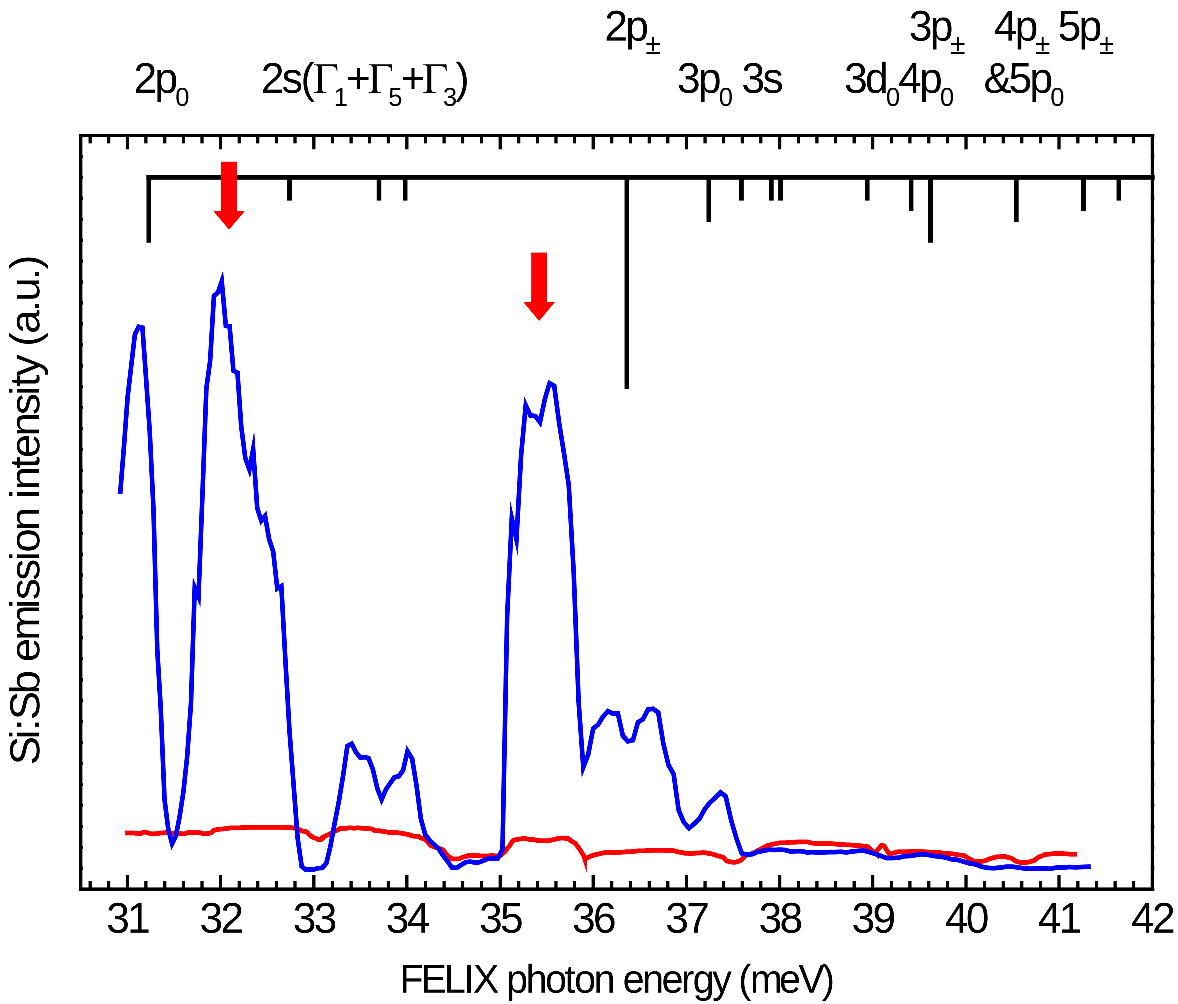
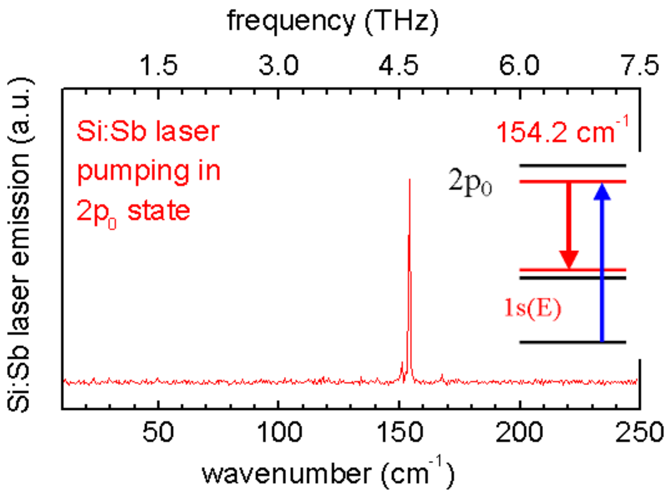
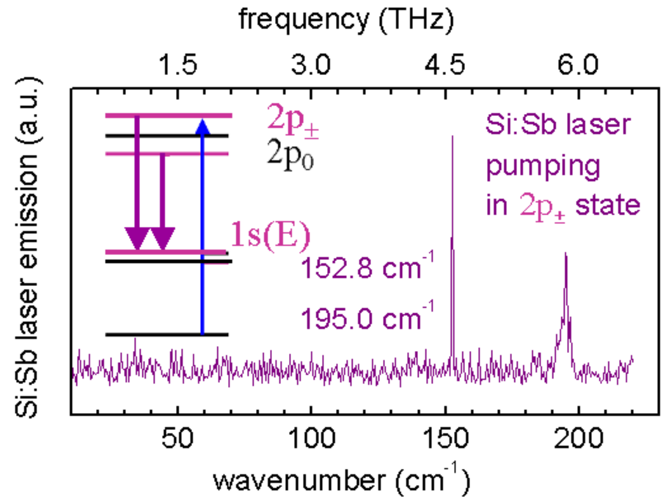
Photoexcitation of Si:Sb: Non-resonant excitation

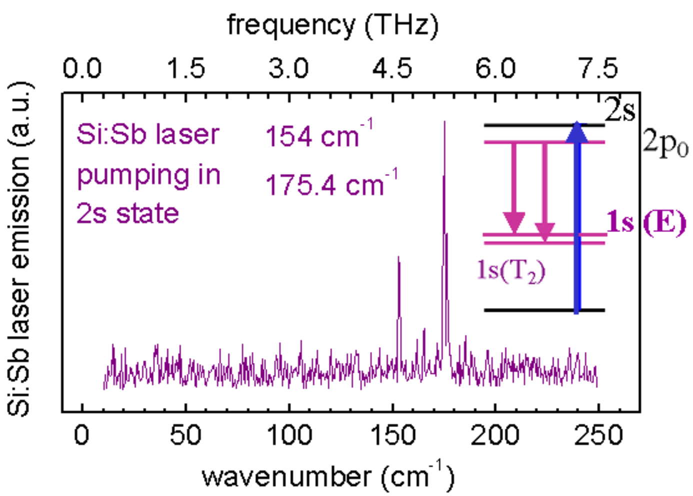


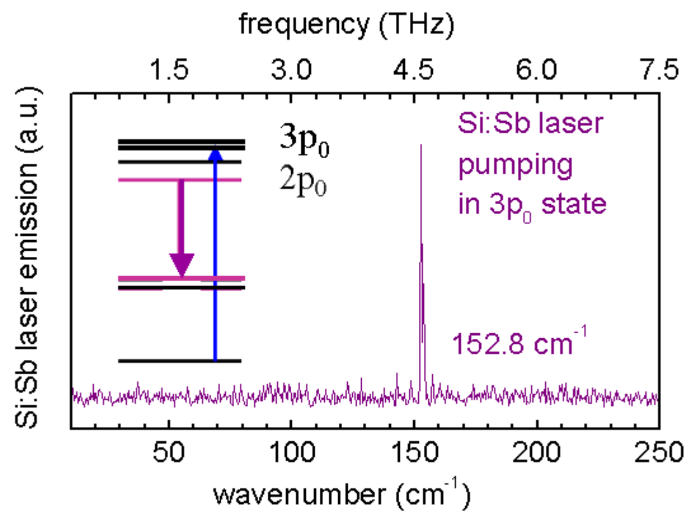
Non-resonant pumping yields laser emission!

Photoexcitation of Si:Sb



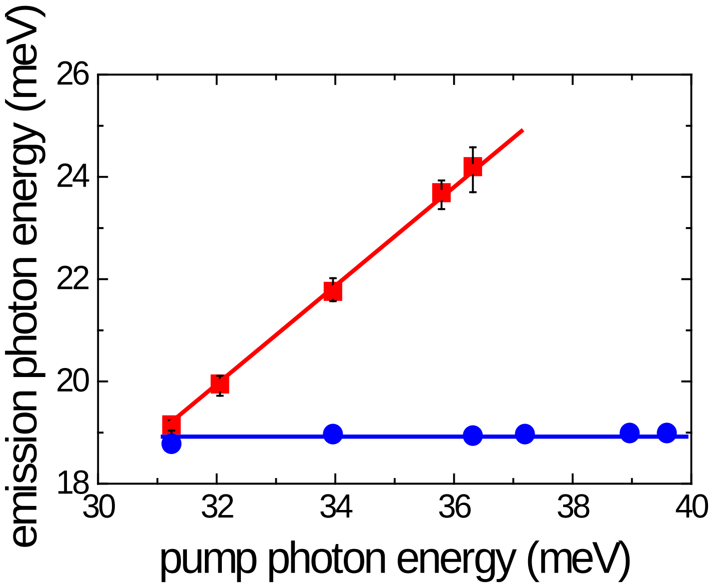




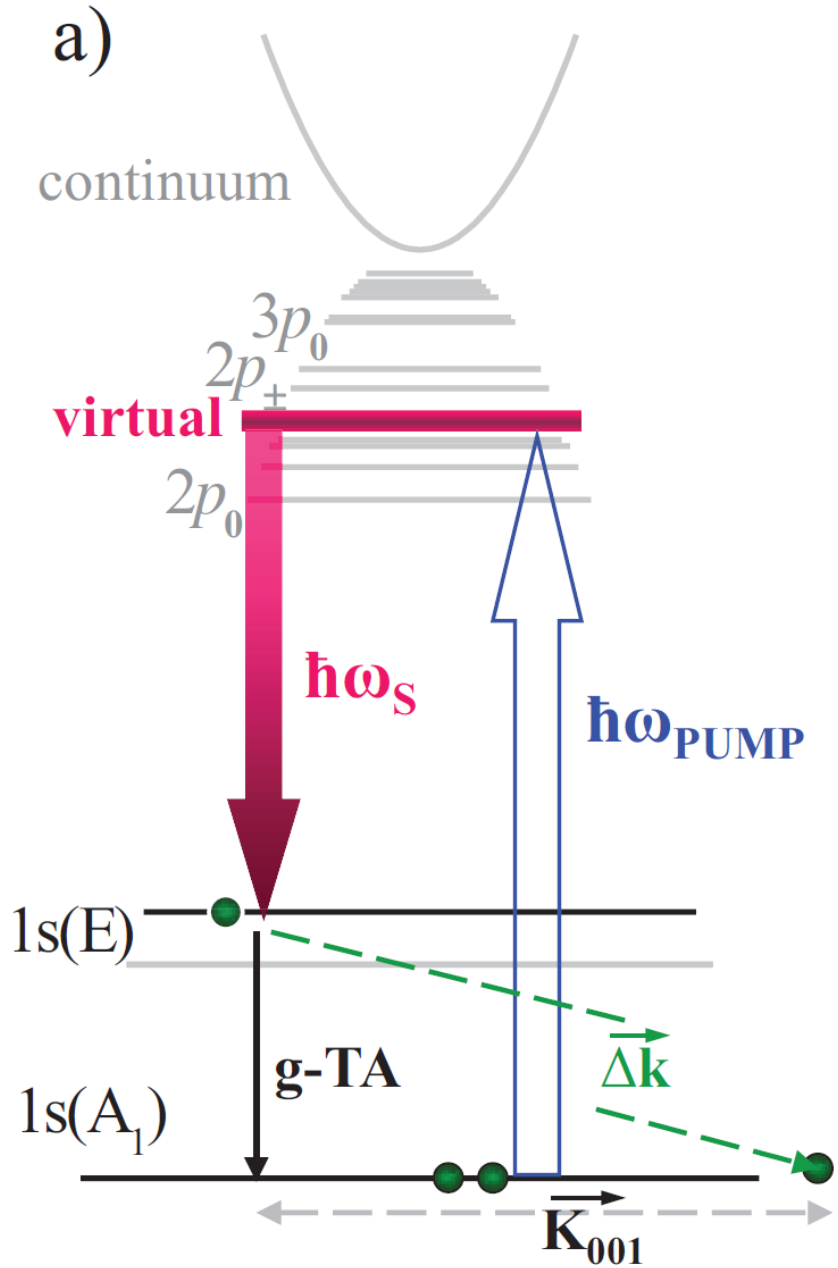


DLR

Si:Sb Raman laser

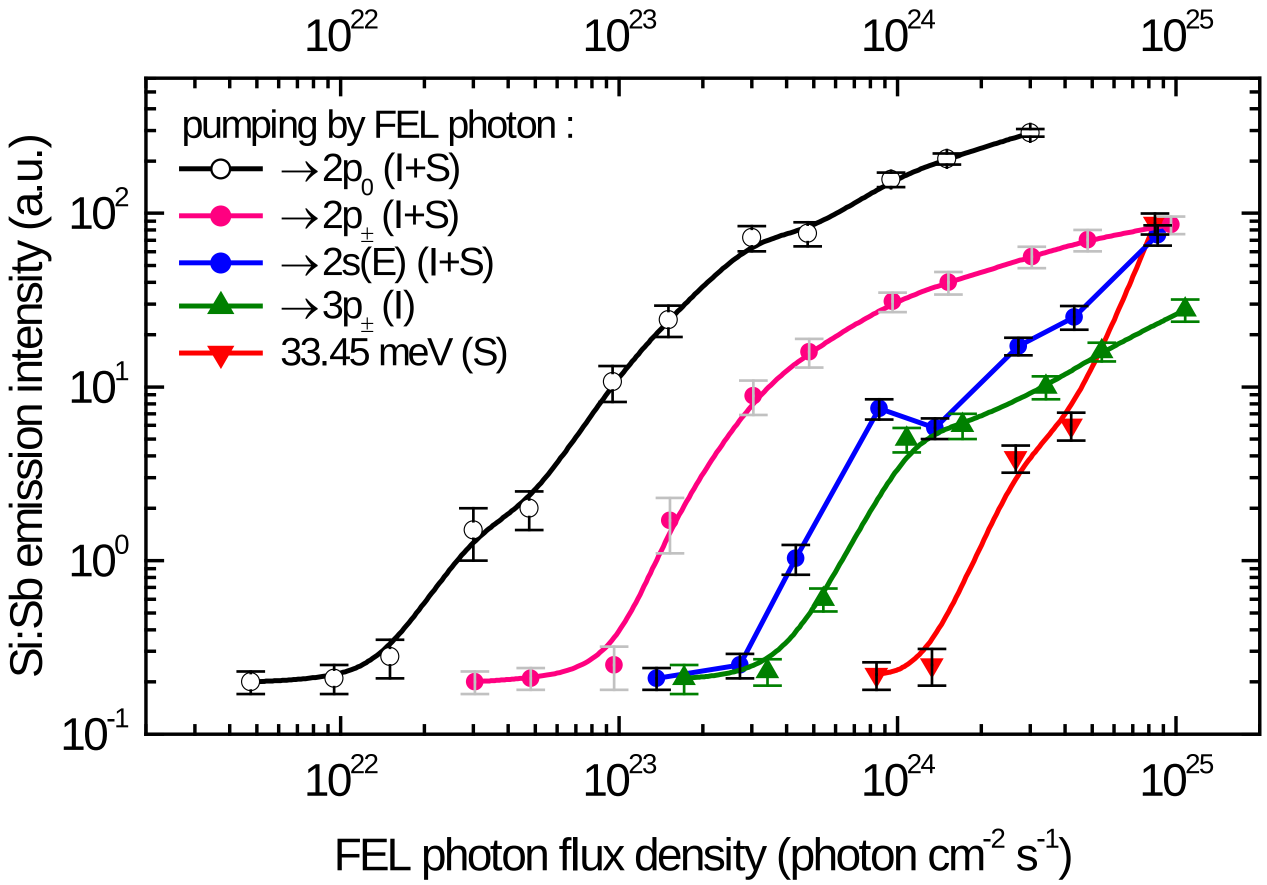


- $h\nu_{emis} = h\nu_{pump}$ - (12.10 ± 0.02) meV
- g-TA phonon: 11.3 - 12.2 meV



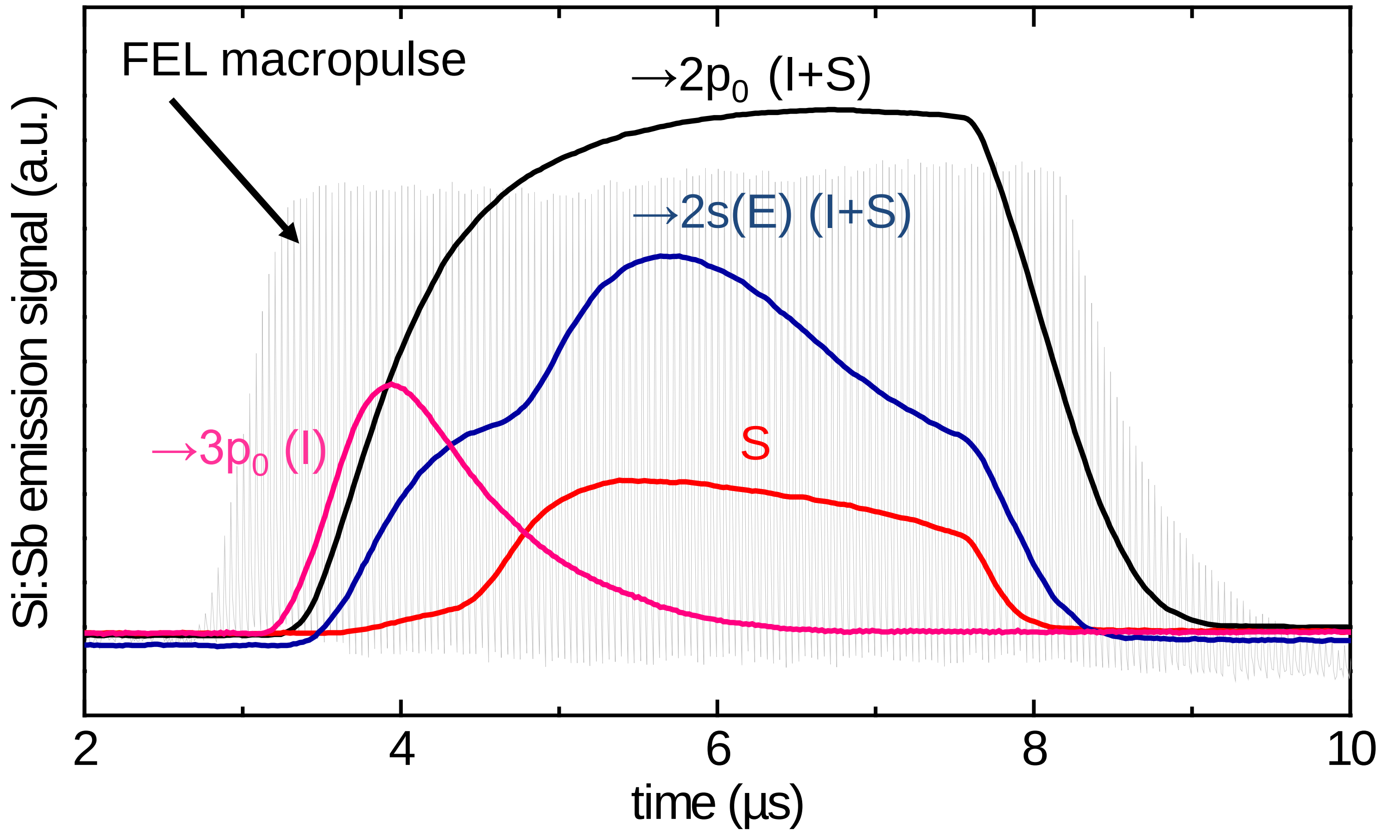
S. Pavlov et al., PRL **96**, 037404 (2006)

Laser threshold of Si:Sb Raman laser



- Threshold for Raman laser / Stokes emission is higher than for donor laser.
- Donor laser saturates with increasing pump power, Raman laser does not.

Emission pulses of the Si:Sb laser

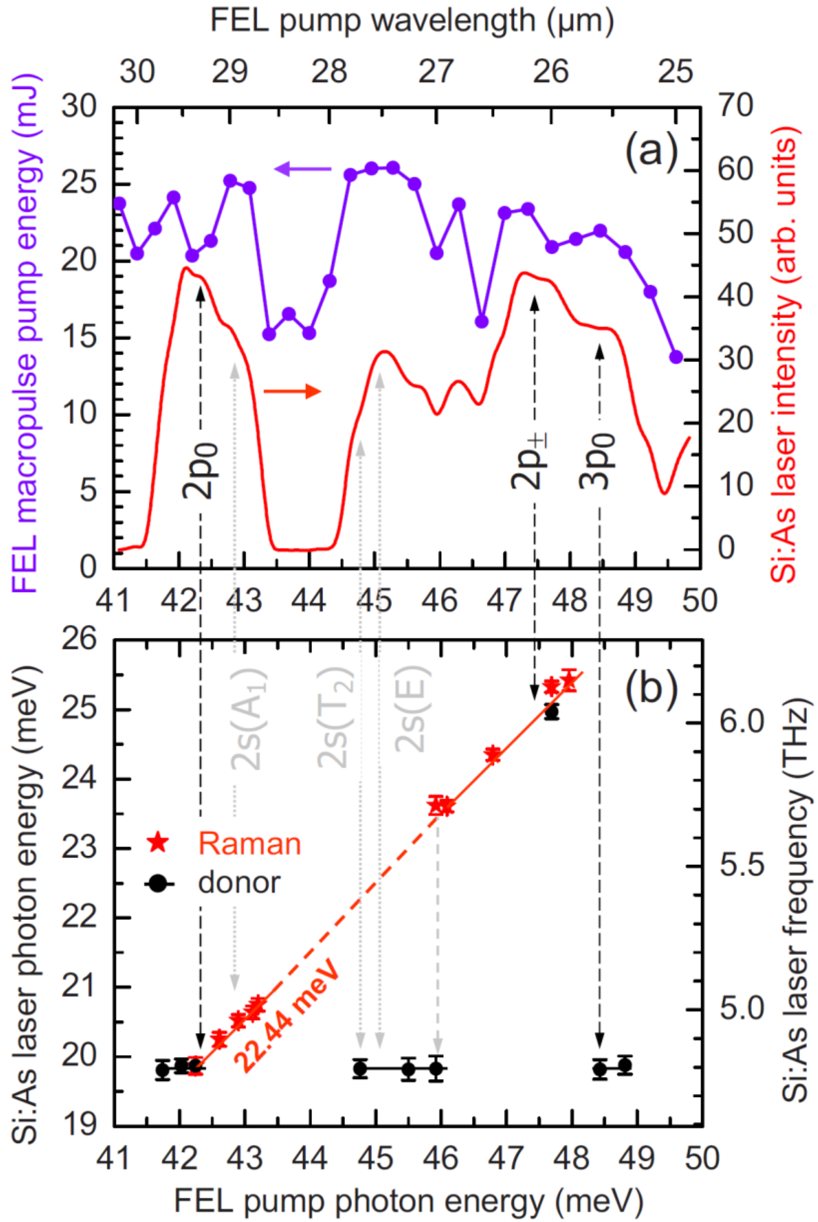


- Raman laser /Stokes emission (S) is delayed wit respect to intracenter donor lasing (I).

Si:As Raman laser

a) FELIX pump spectrum at maximal power (blue) and laser intensity. The minimum at 44 meV is due to strong absorption of the pump radiation by water vapor in the air.

b) Emission frequencies of Raman lasing (red) and donor lasing (black). The Stokes shift of the Raman emission is 22.44 meV.

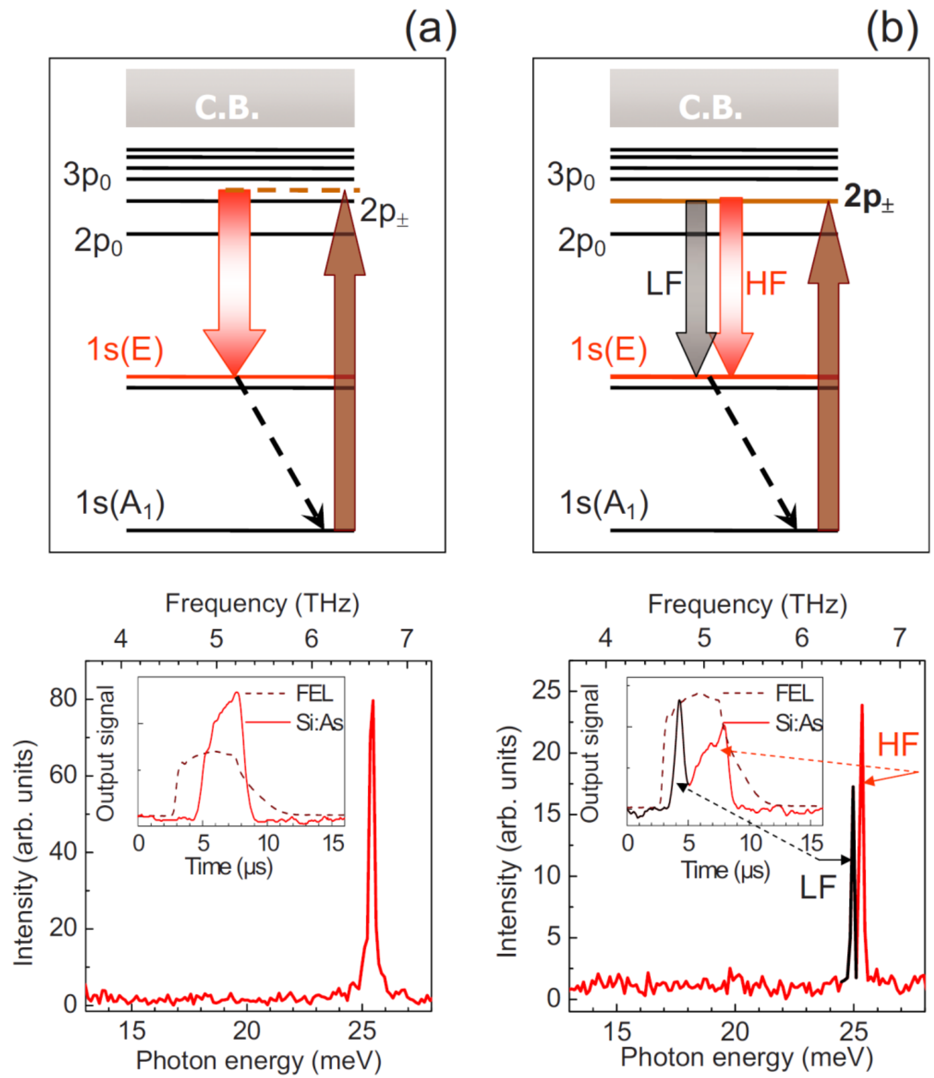


S. Pavlov et al. APL 94, 171112 (2009)

Dynamics of the Si:As laser

a) Pumping between $2p_\pm$ and $3p_0$ states: pure Raman lasing, emission is delayed by about 1.7 µs with respect to the pump pulse.

b) Pumping in vicinity of the $2p_\pm$ state: Combined Raman and donor lasing, donor lasing (black) develops faster (almost no delay with respect to the pump pulse) than Raman lasing (red).



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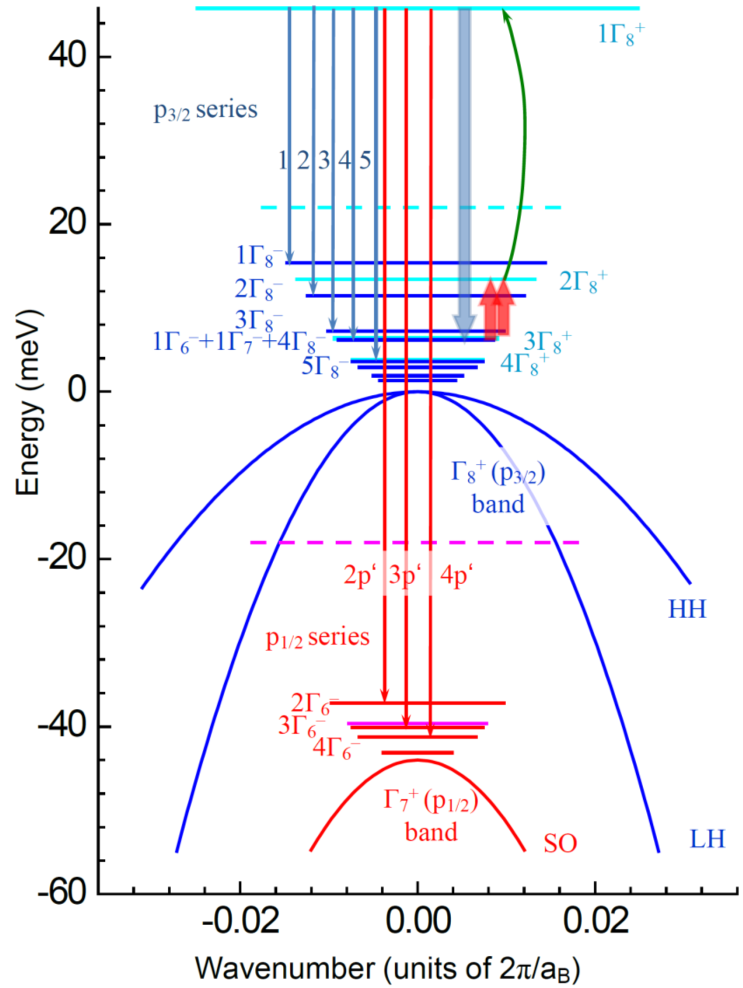
Boron-doped Silicon laser

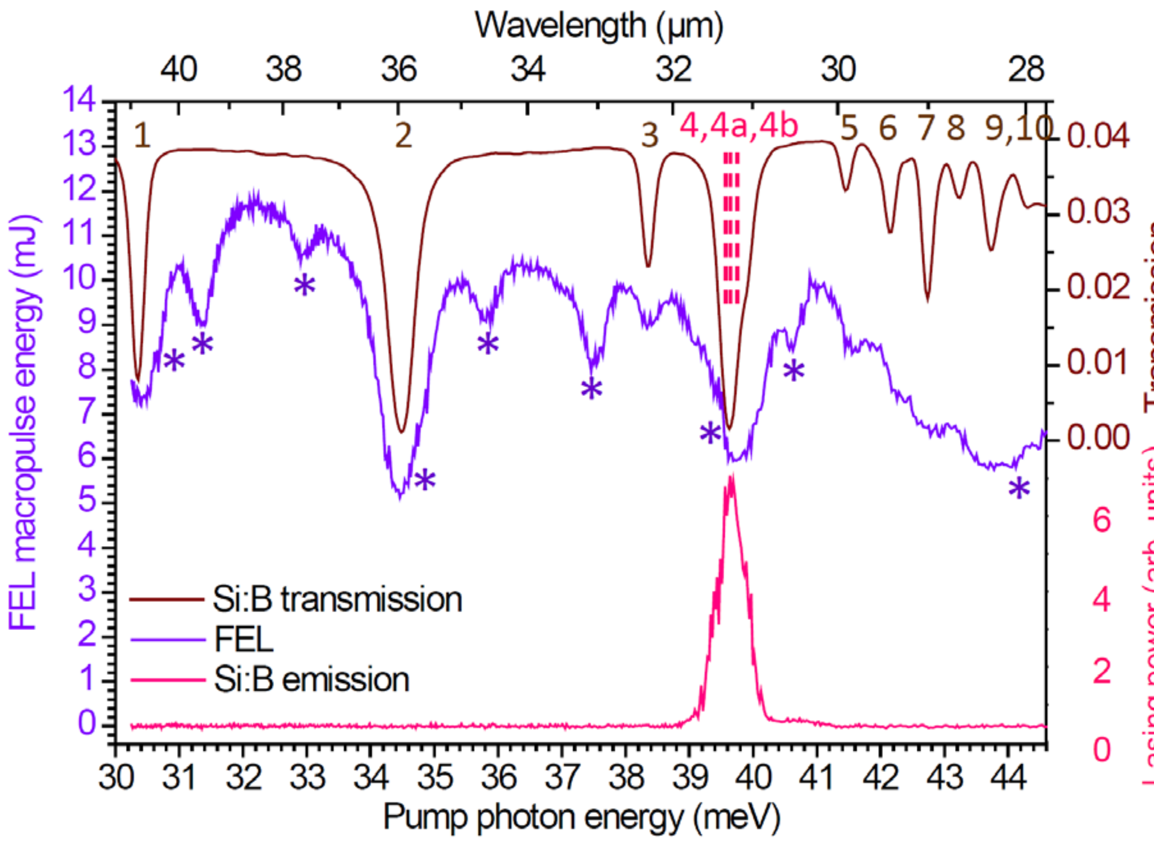
- The $1\Gamma_7^+$ ground state of the split-off state series (Γ_7^+ band) is expected to be between the two horizontal dashed lines.
- Raman spectroscopy: $1\Gamma_7^+$ ground state is at approx. 22 meV
- IR absorption spectroscopy: state not detected



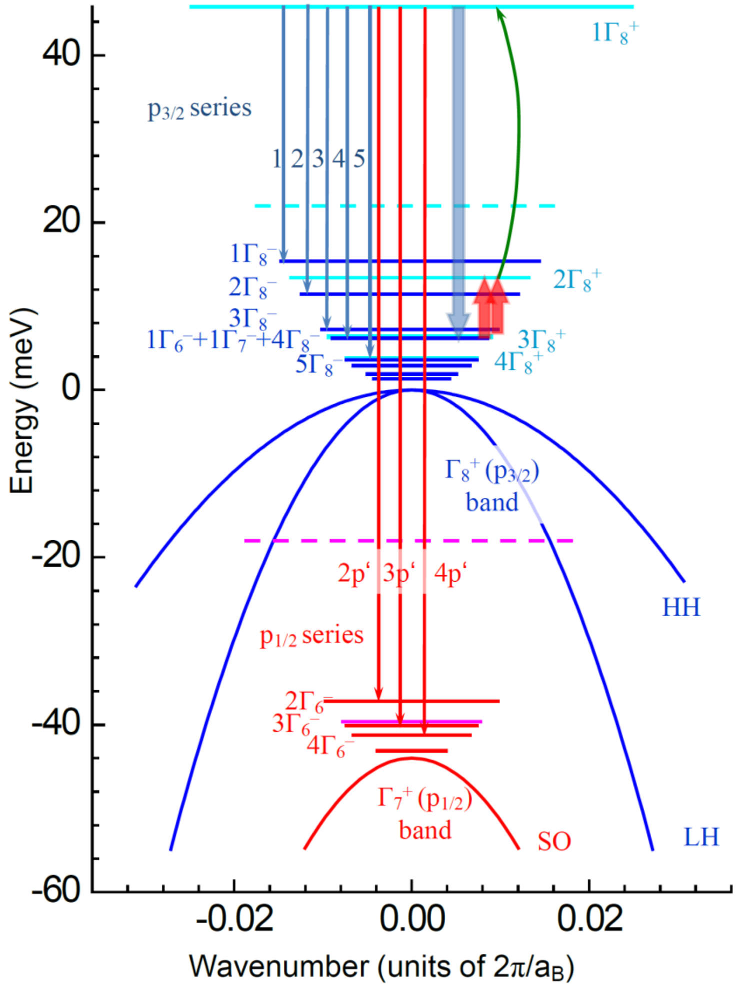
S. Pavlov et al., Phys. Rev. X **4**, 021009 (2014)

Absorption spectrum and laser emission of Si:B

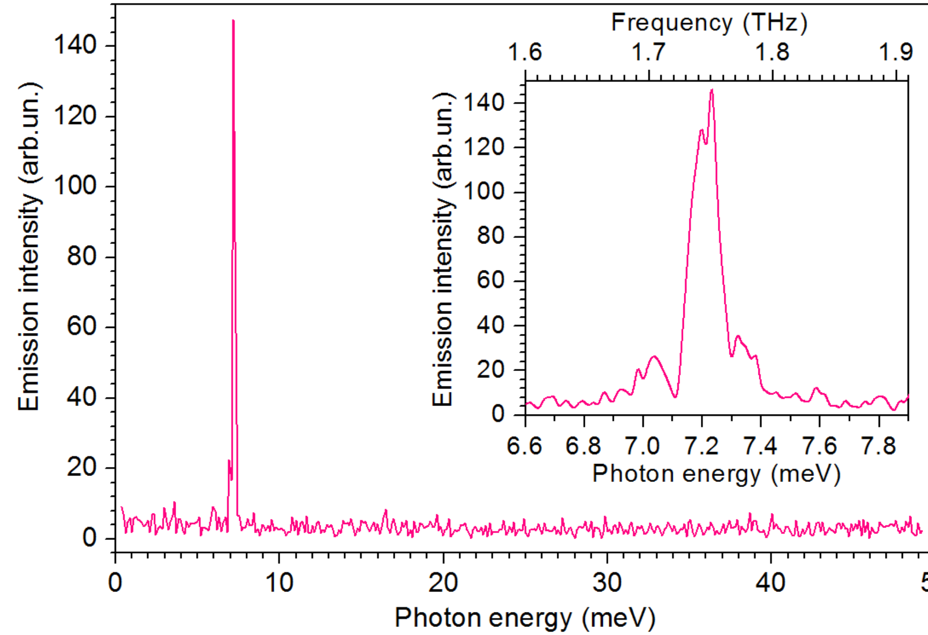
- The absorption spectrum measured with FELIX corresponds to the FTIR spectrum.
- FELIX spectrum is affected by water vapour absorption.
- Only pumping on the boron lines 4, 4a, and 4b results in laser emission.



Emission frequency and threshold

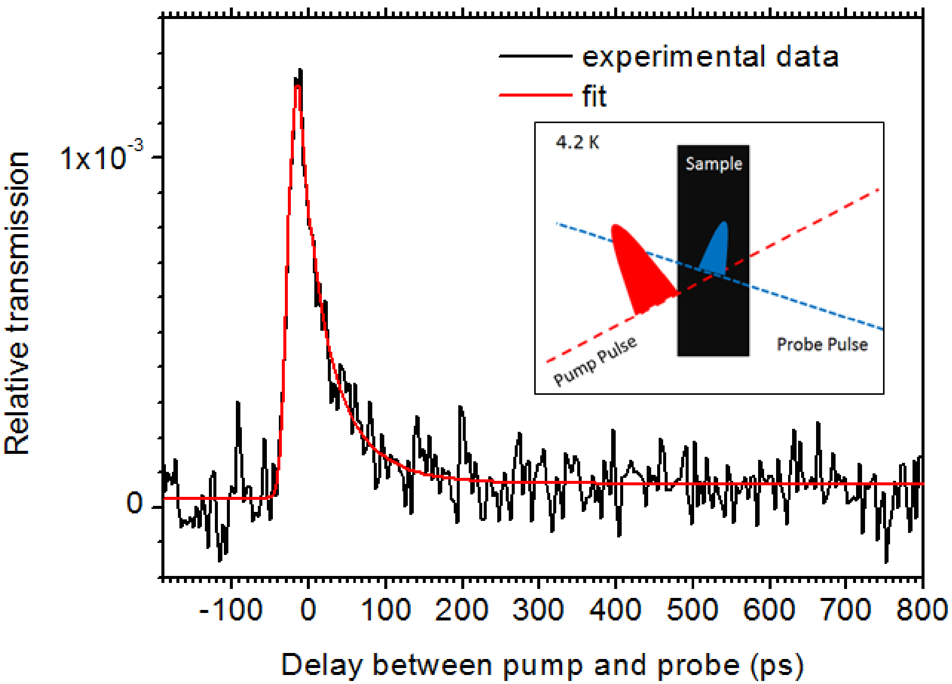


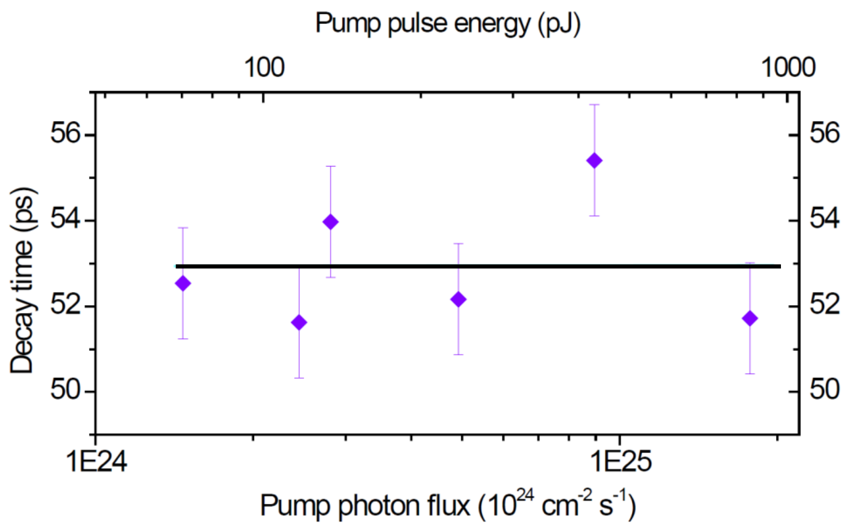
S. Pavlov et al., Phys. Rev. X **4**, 021009 (2014)



- Emission spectrum of the Si:B laser when pumped at the boron line 4.
- Two emission lines at 1.740 THz and 1.748 THz are just resolved.
- Upper laser levels: $1\Gamma_7^-(1p_{5/2})$, $1\Gamma_6^-(1p_{1/2})$
- Lower laser level: $2\Gamma_8^+(1p_{5/2})$

Lifetime of the upper laser level

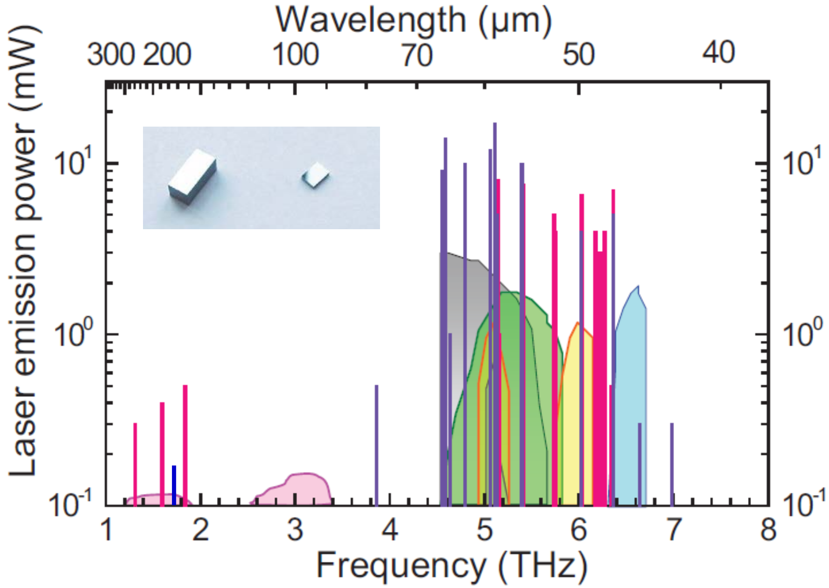




- The short lifetime of the upper laser states (53 ps) limits the laser gain.

Summary and outlook

- Different types of n-type THz Silicon lasers:
    - Intracenter donor laser
    - Raman laser
- n- and p- type lasers
- Laser mechanism is based on the peculiarities of the electron – phonon interaction in Silicon



Future:

- Apply stress to modify electron-phonon interaction
- Deep donors (move to IR)
- Other host material, e.g. C
- Modelling of life times

Thank you for your attention!

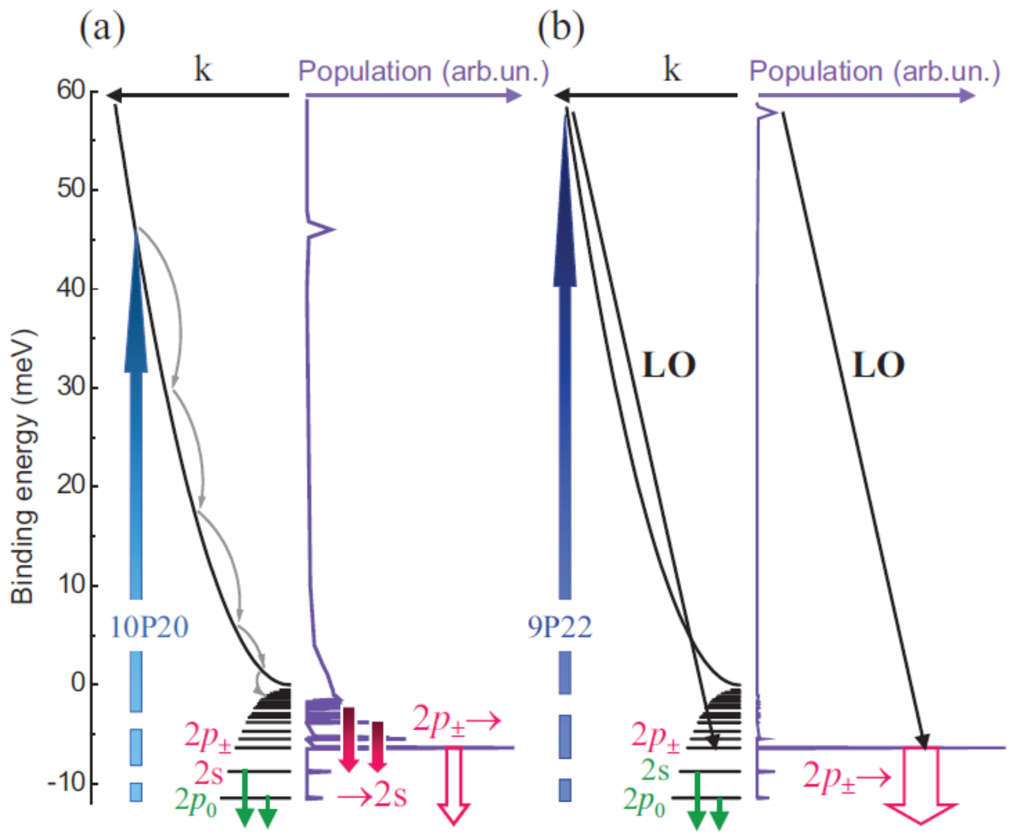
for a review see: S. Pavlov. R. Zhukavin, V. Shastin, H.-W. Hübers, Phys. Status Solidi B 250, 9-36 (2013)

Backup

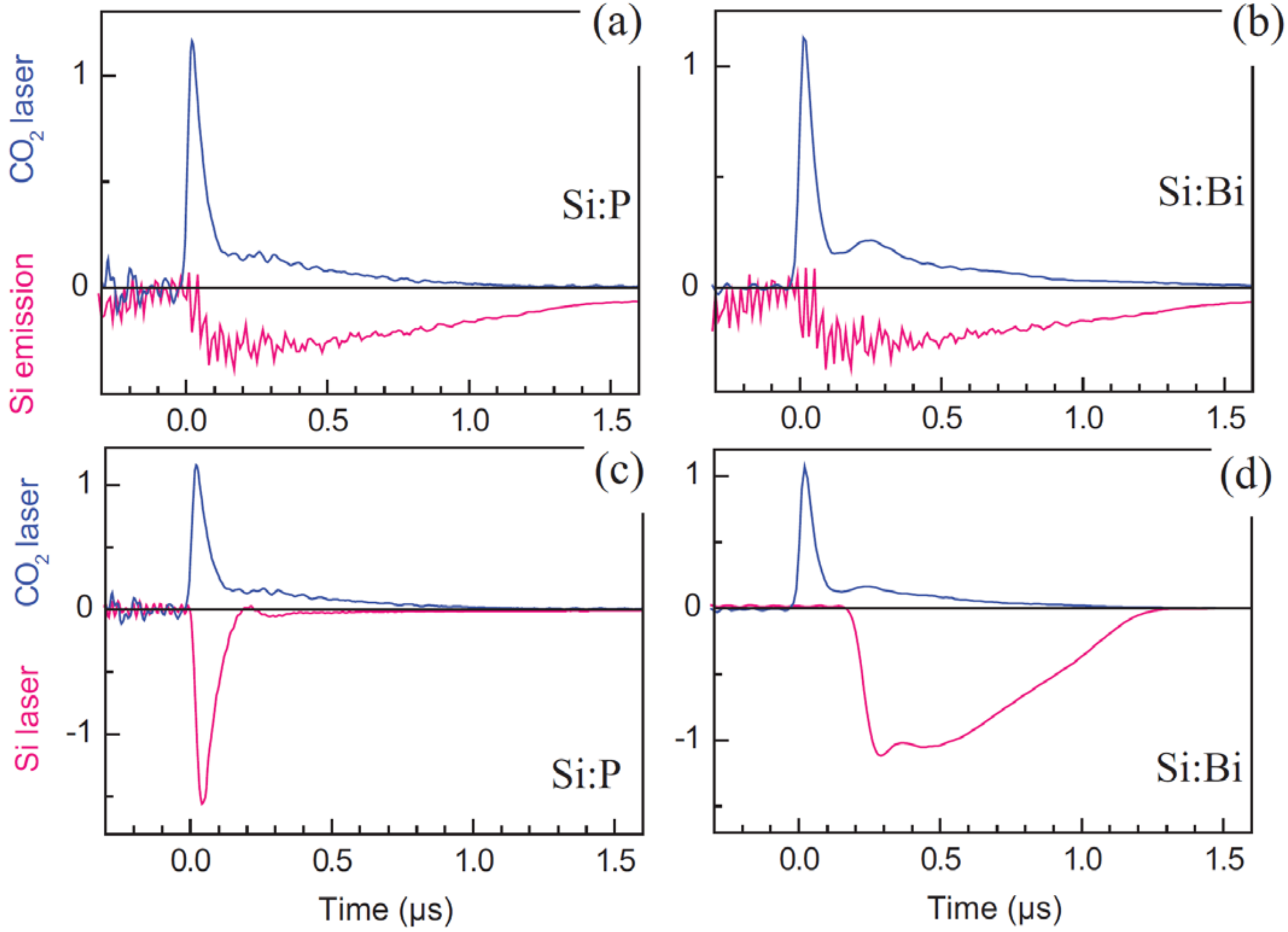
Si:Bi lasers: long-wavelength (~1.5 THz) emission

a) Pumping with 10P20 (117 meV) The laser transitions originate from a number of high excited states and terminate in the long-lived 2s state.

b) Pumping with 9P22 (129 meV): “Shortcut” by the g-LO phonon, only the $2p_{\pm}$ state has a significant population and the laser transitions are $2p \rightarrow 1s(E)$, $1s(T_2)$.



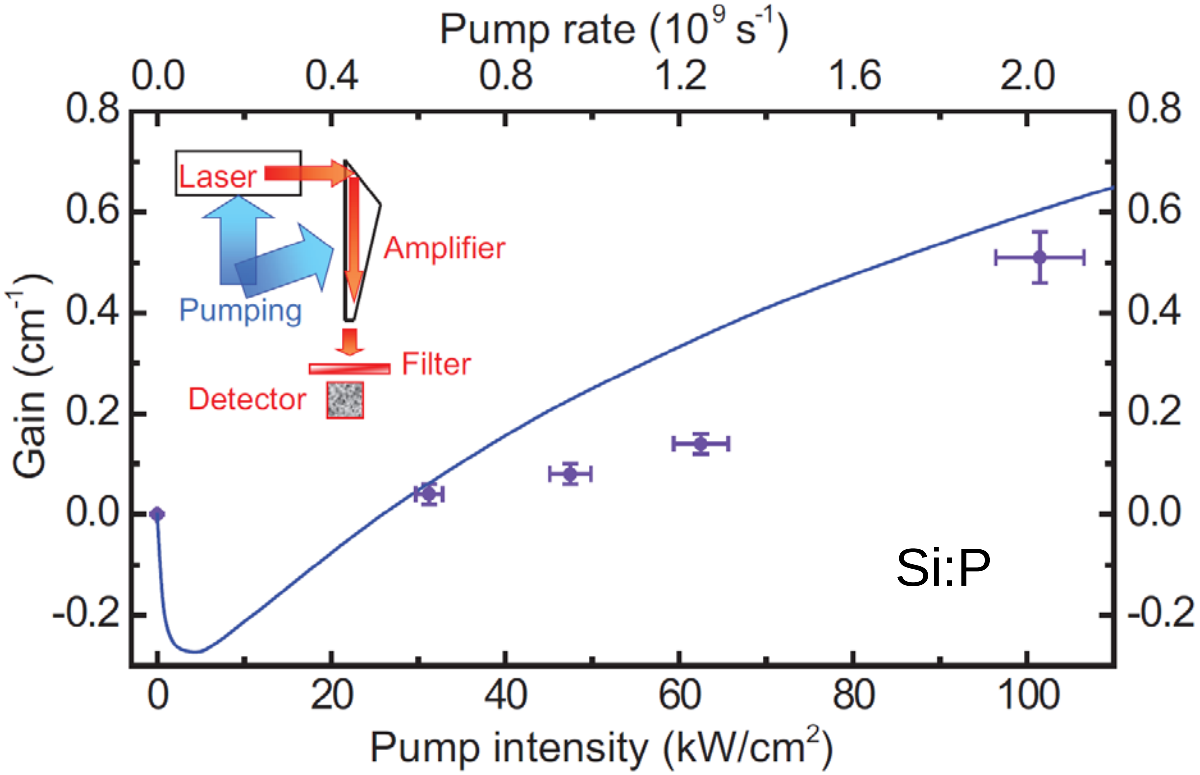
Laser dynamics



Below laser threshold (Si emission x1000)

Above laser threshold

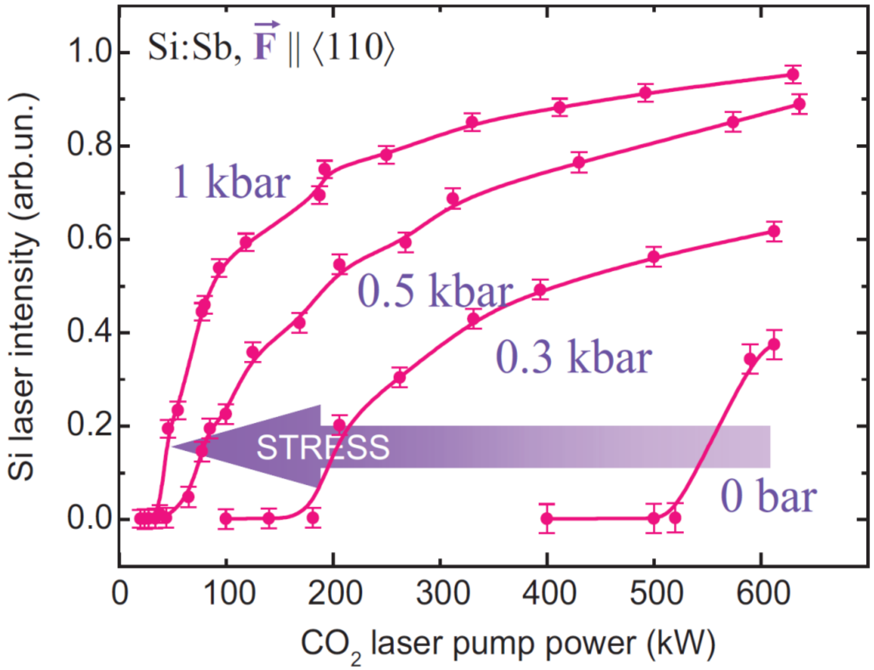
Laser gain

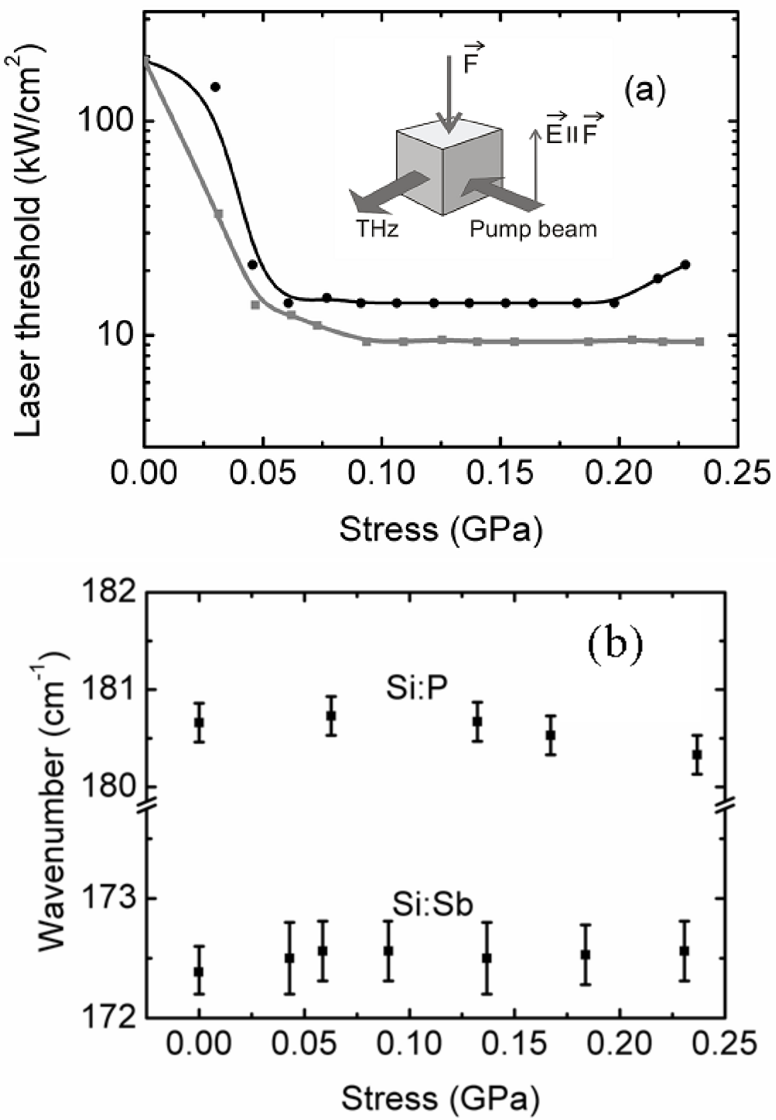


- Gain of Si:P laser: up to 0.5 cm^{-1}
- Gain of Si:Bi laser: 0.005 – 0.02 cm^{-1} (estimated from laser pulse delay, 9P-pumping has higher gain than 10P pumping))

R.Zhukavin et al., JAP 102, 093104 (2007)

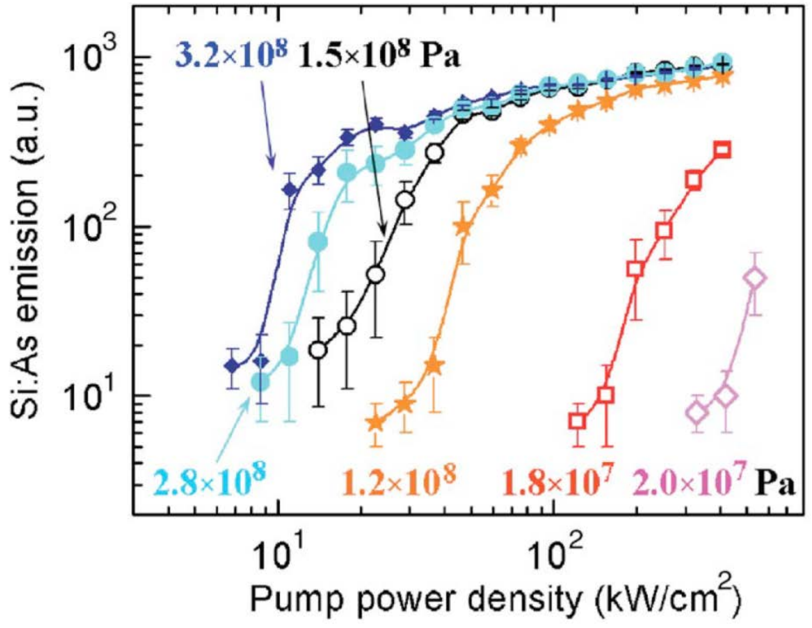
Compressive force / stress

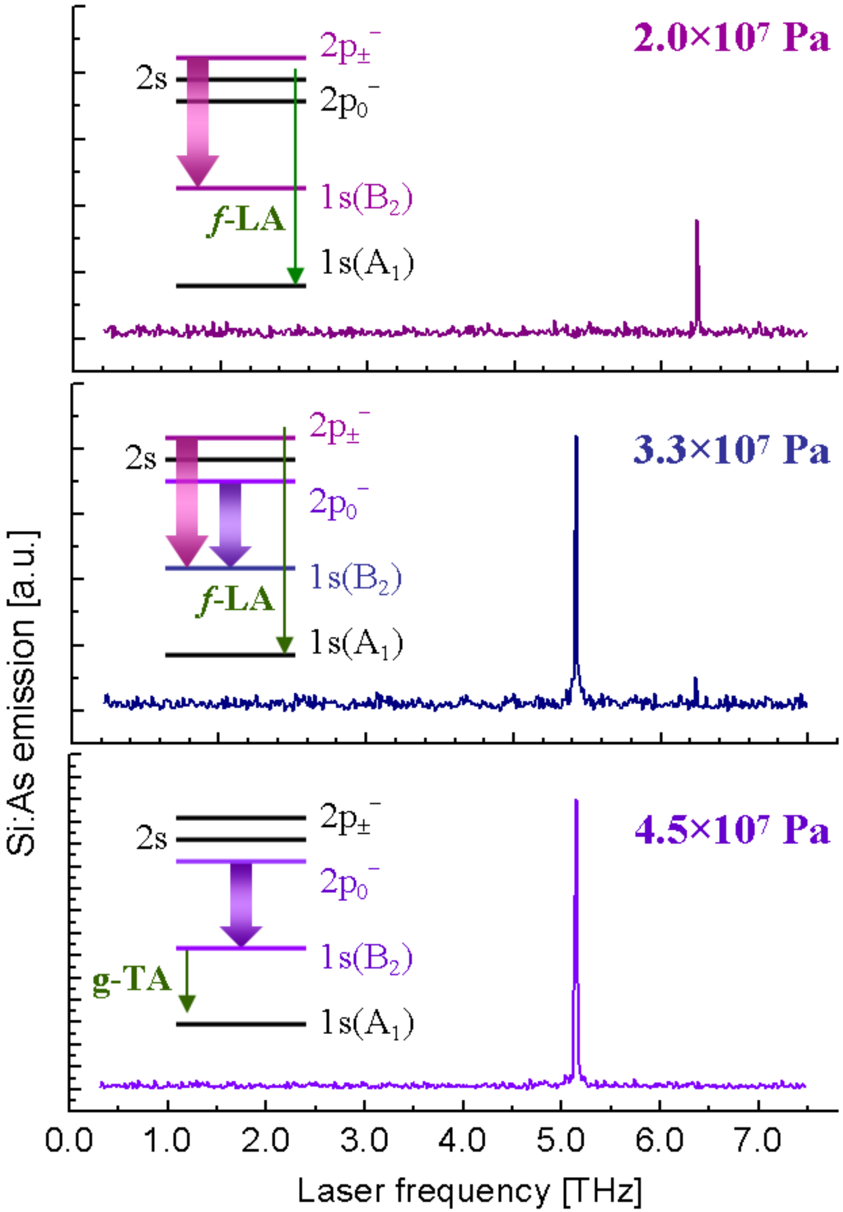




- Up to 0.1 GPa the laser threshold decreases with stress
- The laser frequency is not affected

Stressed Si:As laser

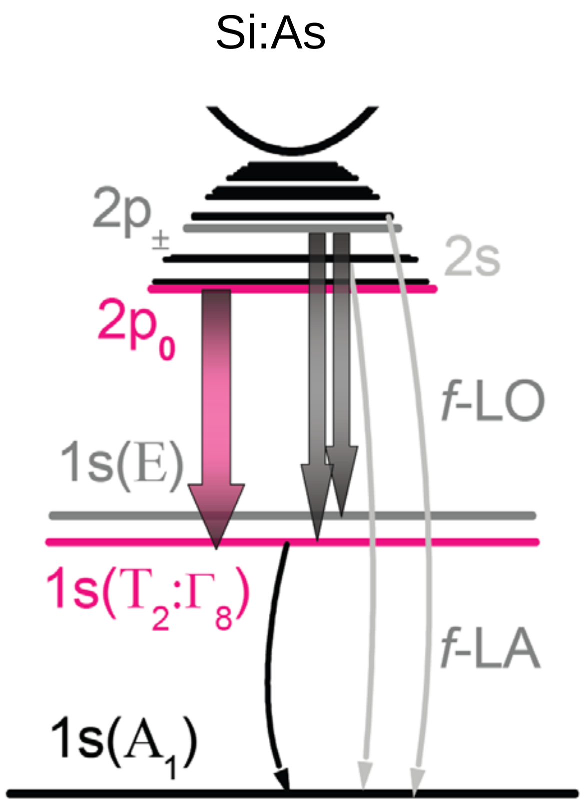


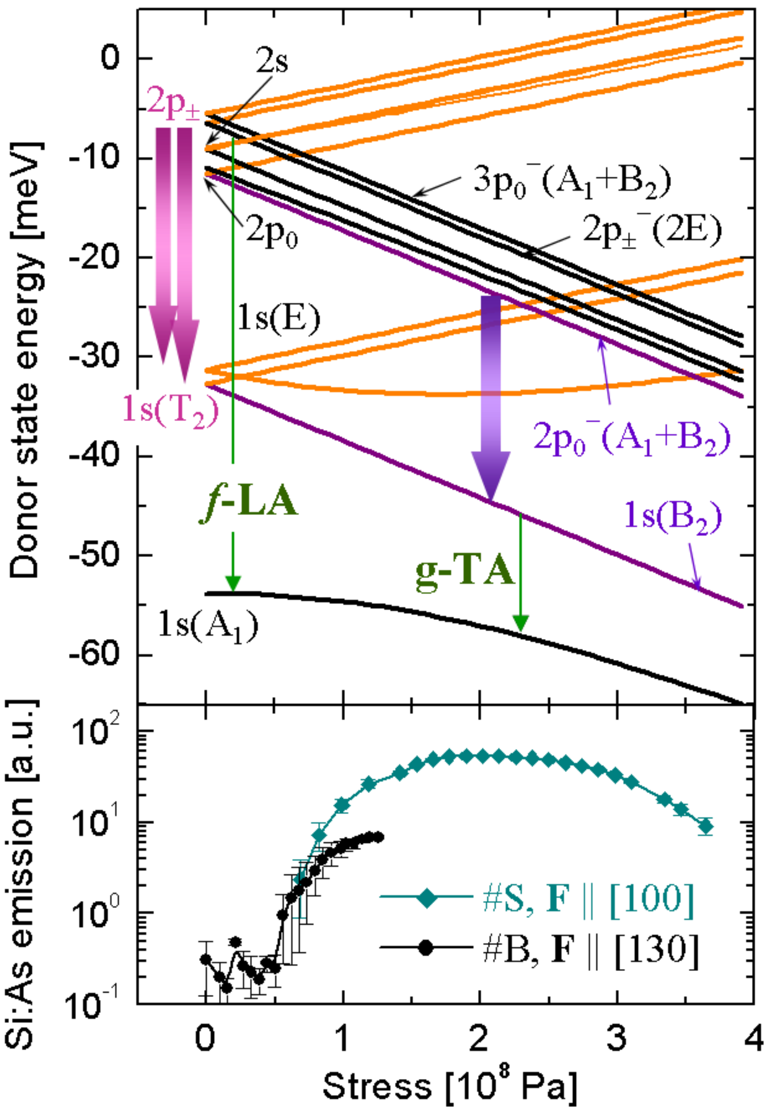


- Lowering of laser threshold by ~100
- Change of emission spectrum
- Si:As laser becomes Si:P-like

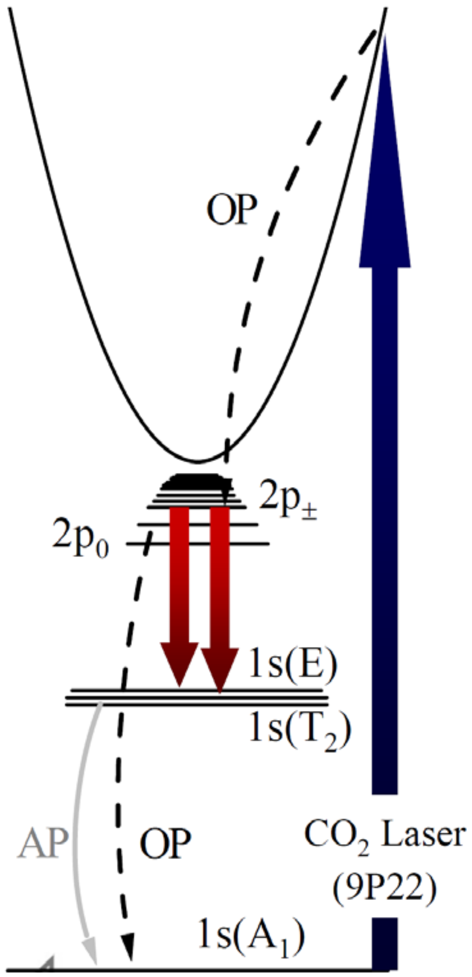
APL 94, 171112, (2009)

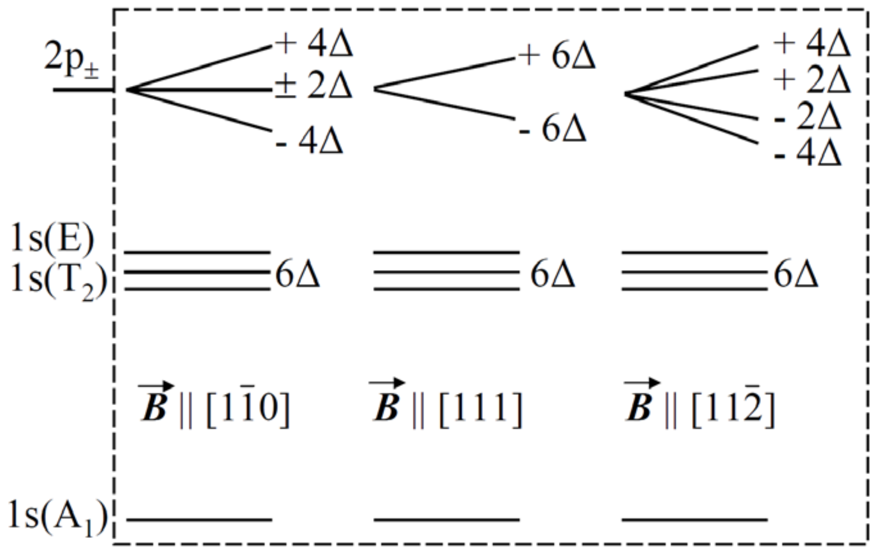
Stressed Si:As laser





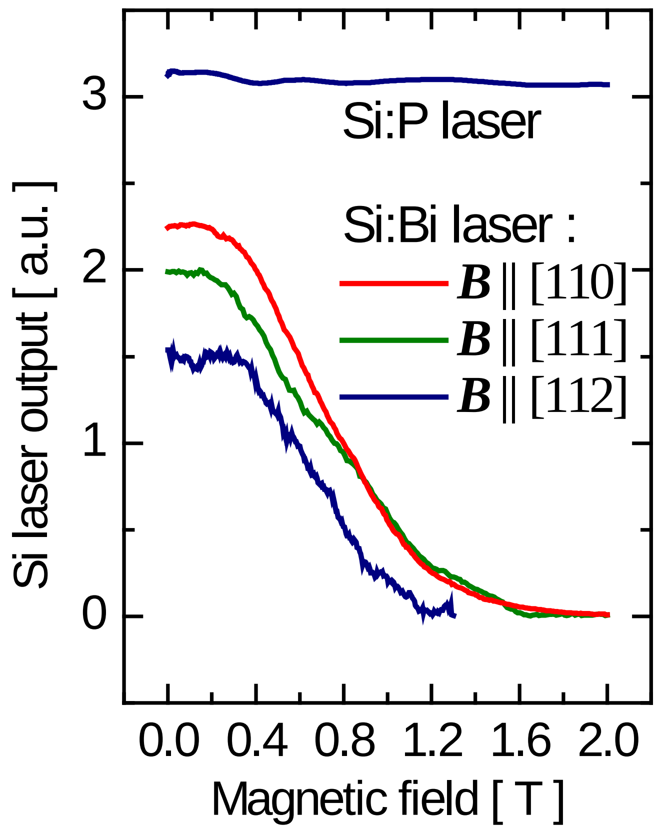
Si:Bi laser in a magnetic field

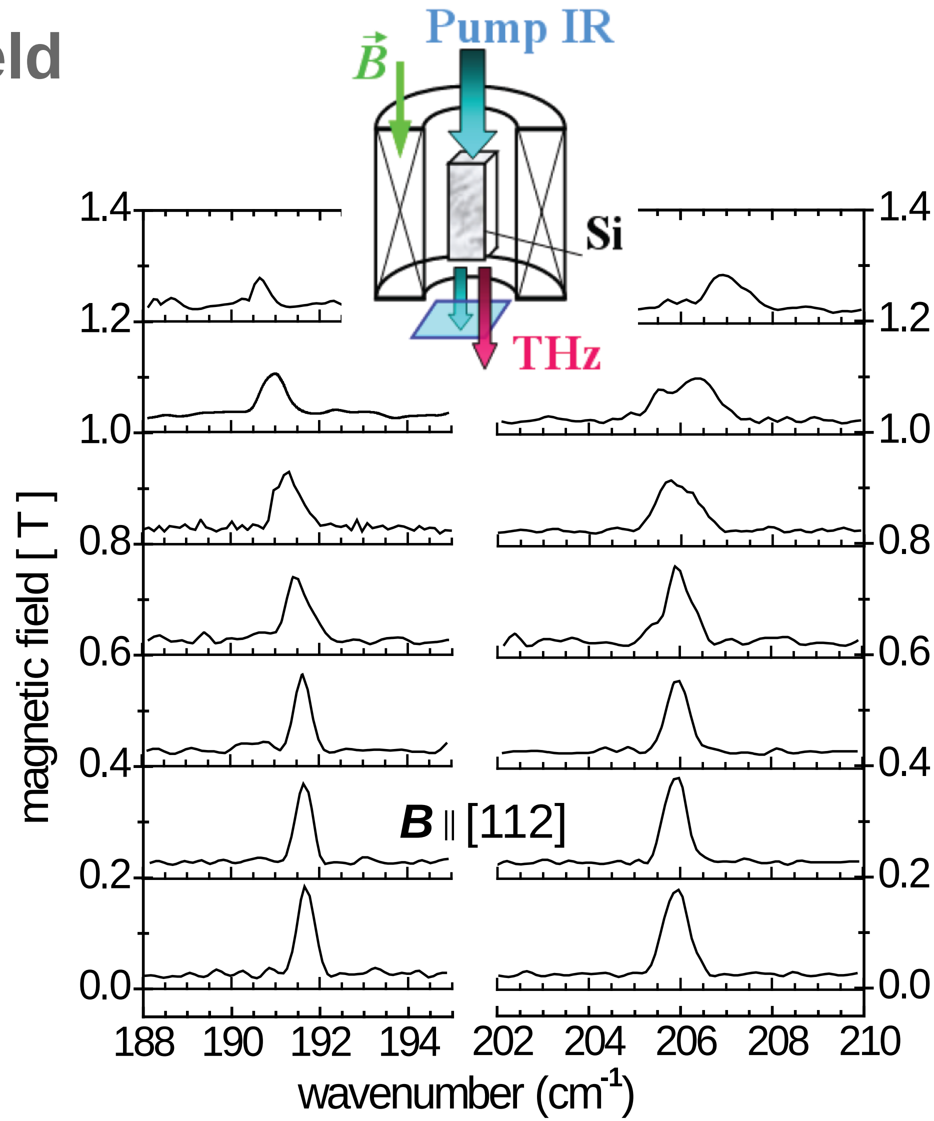




Scheme of the linear Zeeman effect in Si:Bi (not to scale): Splitting of the $2p_{\pm}$ impurity state; 2, 4, and 6 are the states, which originate from the $2p_{\pm}$ state (different valleys of the conduction band, different orientations of the magnetic field relative to the crystal axis). Note that all *s*-type and np_0-type states do not exhibit splitting.

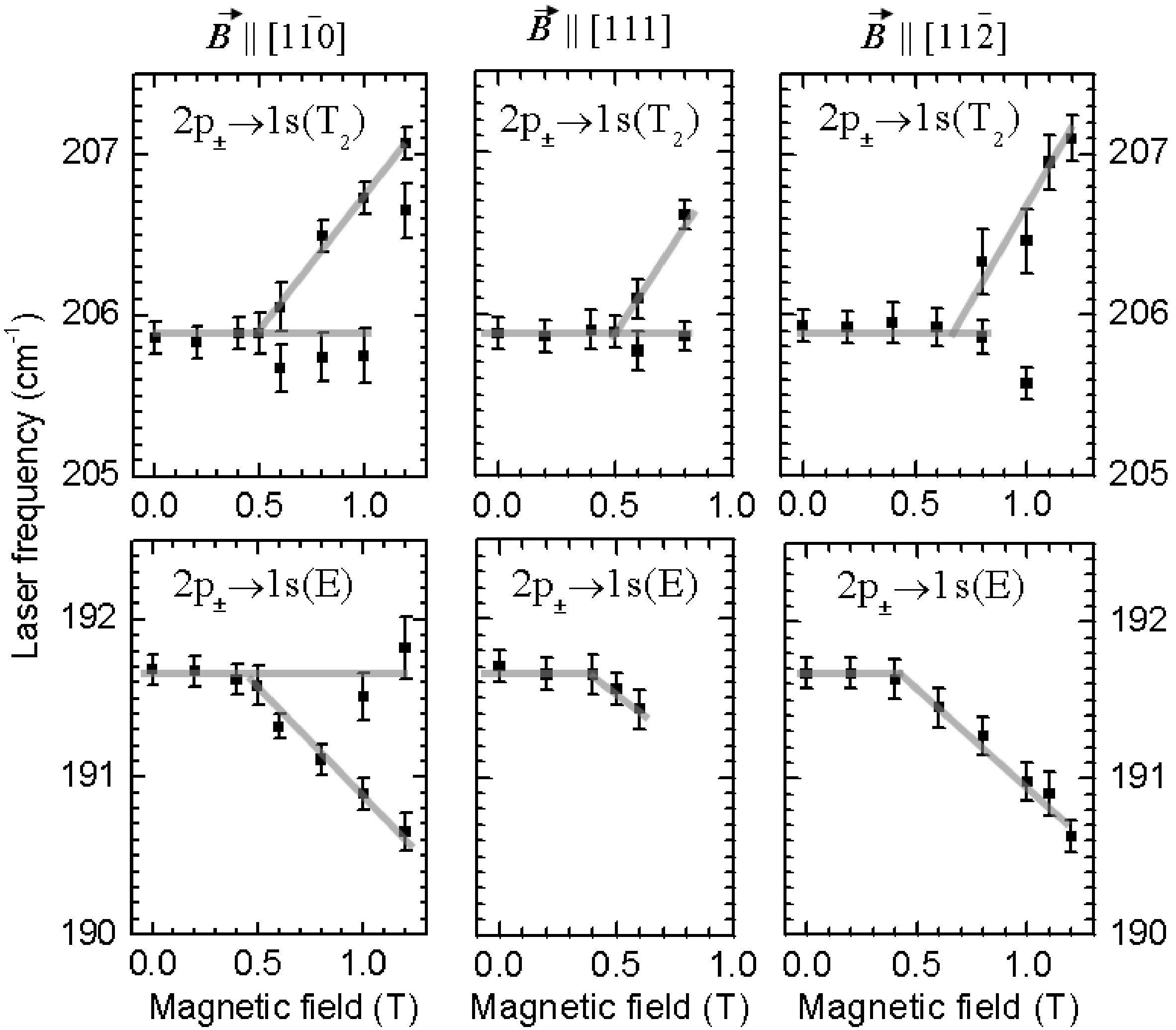
Si:Bi laser in a magnetic field





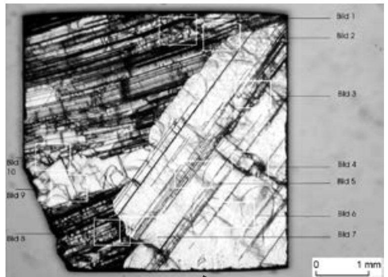
APL **89**, 021108 (2006)

Frequency tunability and crystal orientation



∂f/∂B ~ 40-60 GHz/T (expected from linear Zeeman effect)

Si:P lasers based with different crystal quality

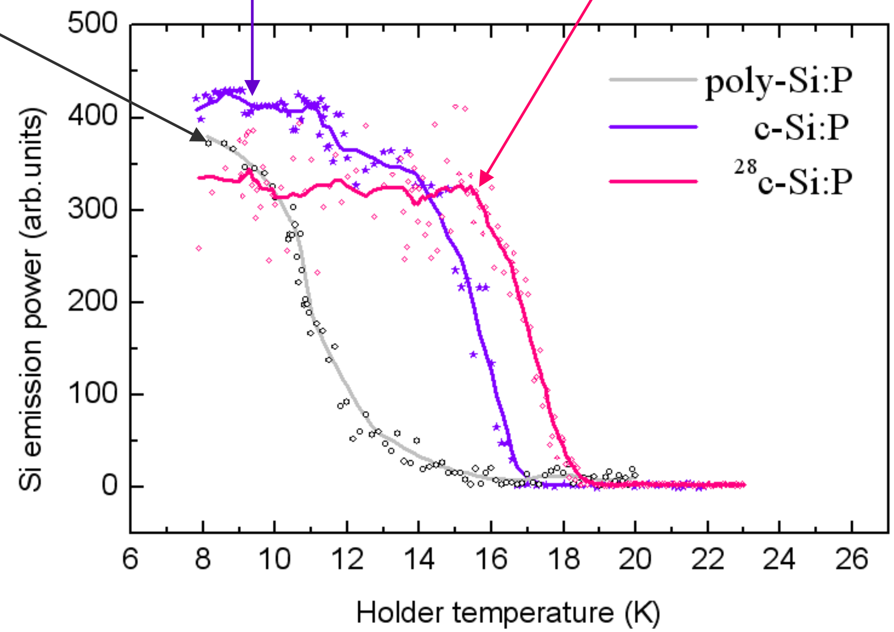


mc-Si

c-^{nat}Si

c-^{28}Si

- ^{28}Si lasers operate at the highest heat sink temperature(best heat conductivity)
- Polycrystalline Si works also.



unpublished

Boron-doped silicon

PHYSICAL REVIEW B VOLUME 39, NUMBER 9 15 MARCH 1989-II

Spin-orbit splitting of the valence bands in silicon determined by means of high-resolution photoconductive spectroscopy

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(Received 8 November 1988)

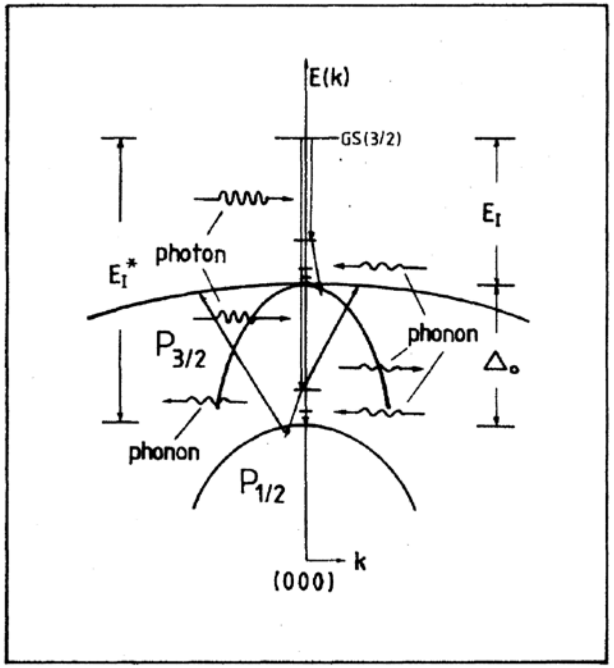

FIG. 1. Schematic diagram showing photoconductive processes of an acceptor in silicon.

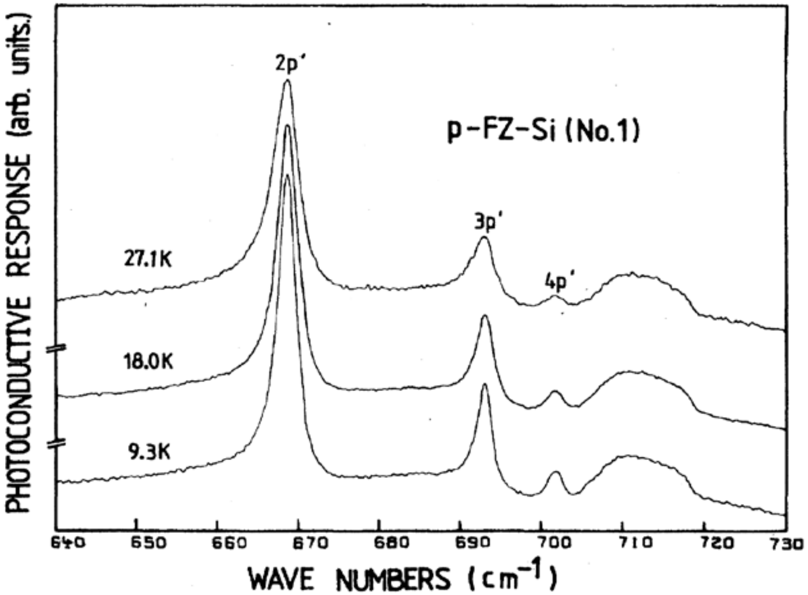

FIG. 2. High-resolution photoconductive spectra of sample No. 1 (room-temperature resistivity is 1000 Ω cm) at 9.3, 18.0, 27.1 K. (The continuous bands of the curves have exactly the same shape for demonstrating the temperature dependence of the peaks). Instrumental resolution is 0.25 cm^{-1}.