Magnetic Field Tuning of Electron-Electron Interactions

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Content

Motivation

Design structures to influence e-e- scattering

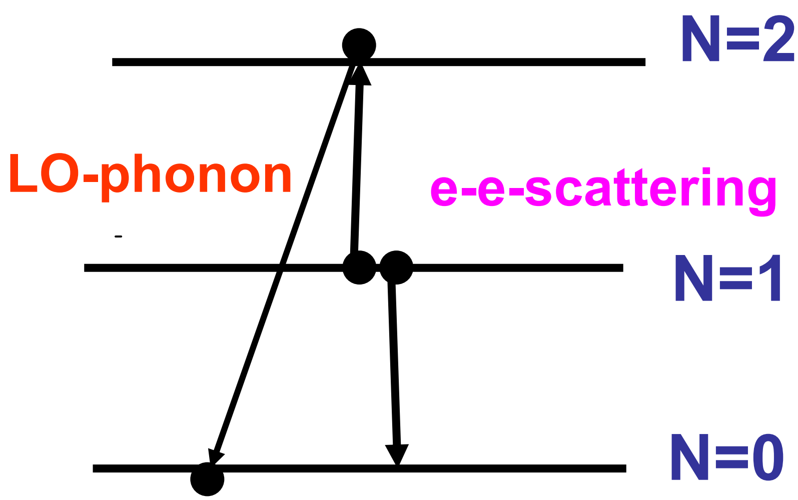
QCL: Reduce e-e-interaction by magnetic field

Intersubband plasmons: use e-e interaction to generate a plasmon instability

- Experimental work on quantum well samples
- Emission results

Summary

Joint paper Phys.Rev. 1978 with Bruce on electron-electron scattering rates between Landau levels in bulk InSb, GaAs and CdTe

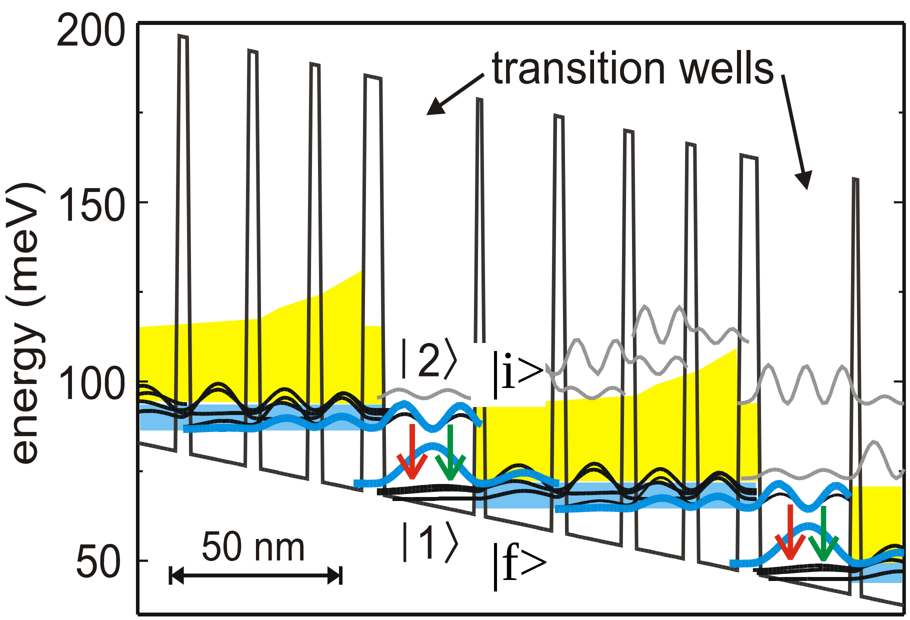


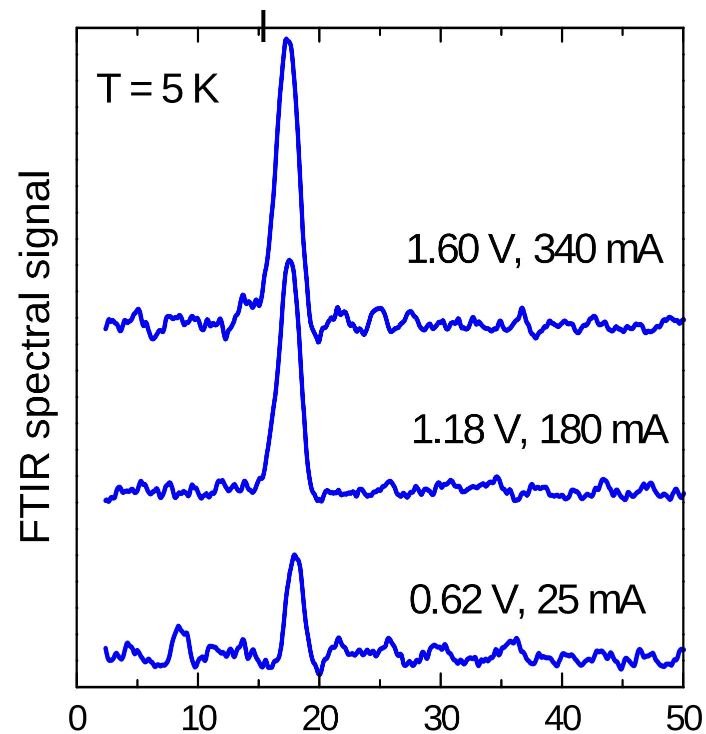
Quantization only in xy direction not in the direction of magnetc field

- energies E0 and E1 below the LO-resonance: (E_{if} < 36 meV)
- non-radiative channel:
  - e-e-scattering
- depopulation of final state E2 through LO-phonon emission

THz quantum cascade structure

conduction band structure

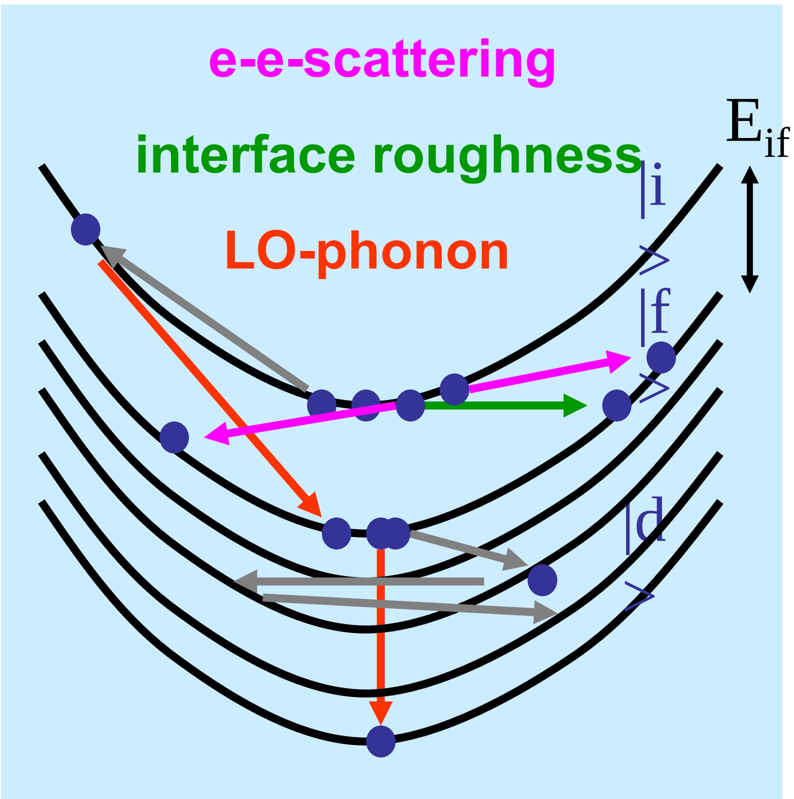




radiative transitions: $\hbar\omega = 17\ meV \quad \upsilon = 4.1\ THz$

unwanted non-radiative transitions limit the emission efficiency

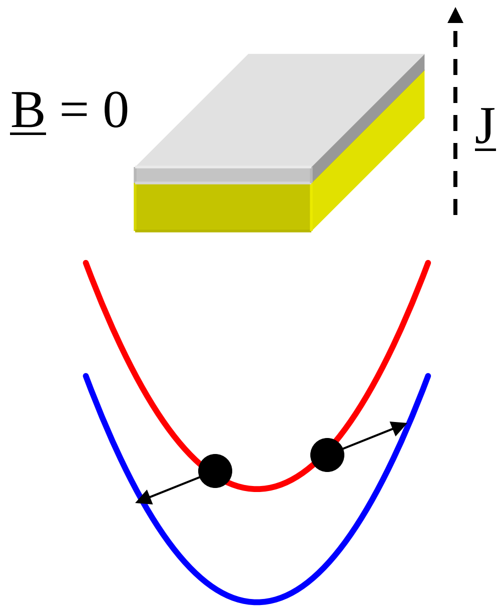
Scattering mechanisms - non-radiative processes



- energy below the LO-resonance: (E_{if} < 36 meV)
- non-radiative channels:
  - phonon emission from heated electrons
  - interface roughness scattering
  - e-e-scattering
- depopulation of final state |f>
  - LO-phonon emission
  - intraminiband tunneling extraction

in-plane quantization / quantum box structure

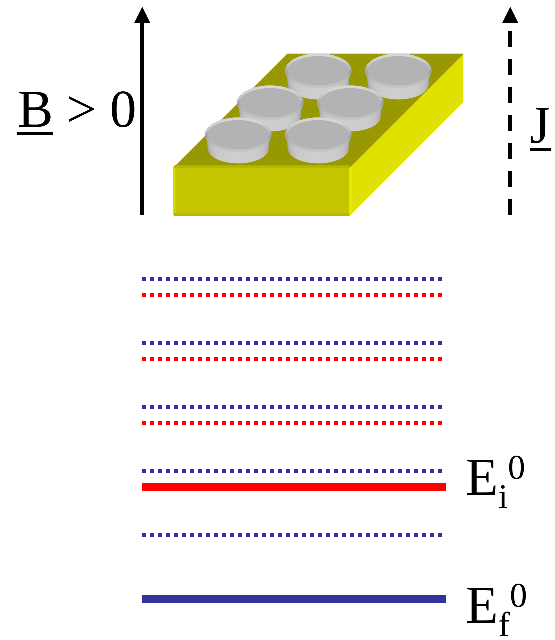
no magnetic field



continuous energy spectrum

$$E_j = E_j^0 + \frac{\hbar^2 k_{//}^{\ 2}}{2m^*}$$

perpendicular magnetic field



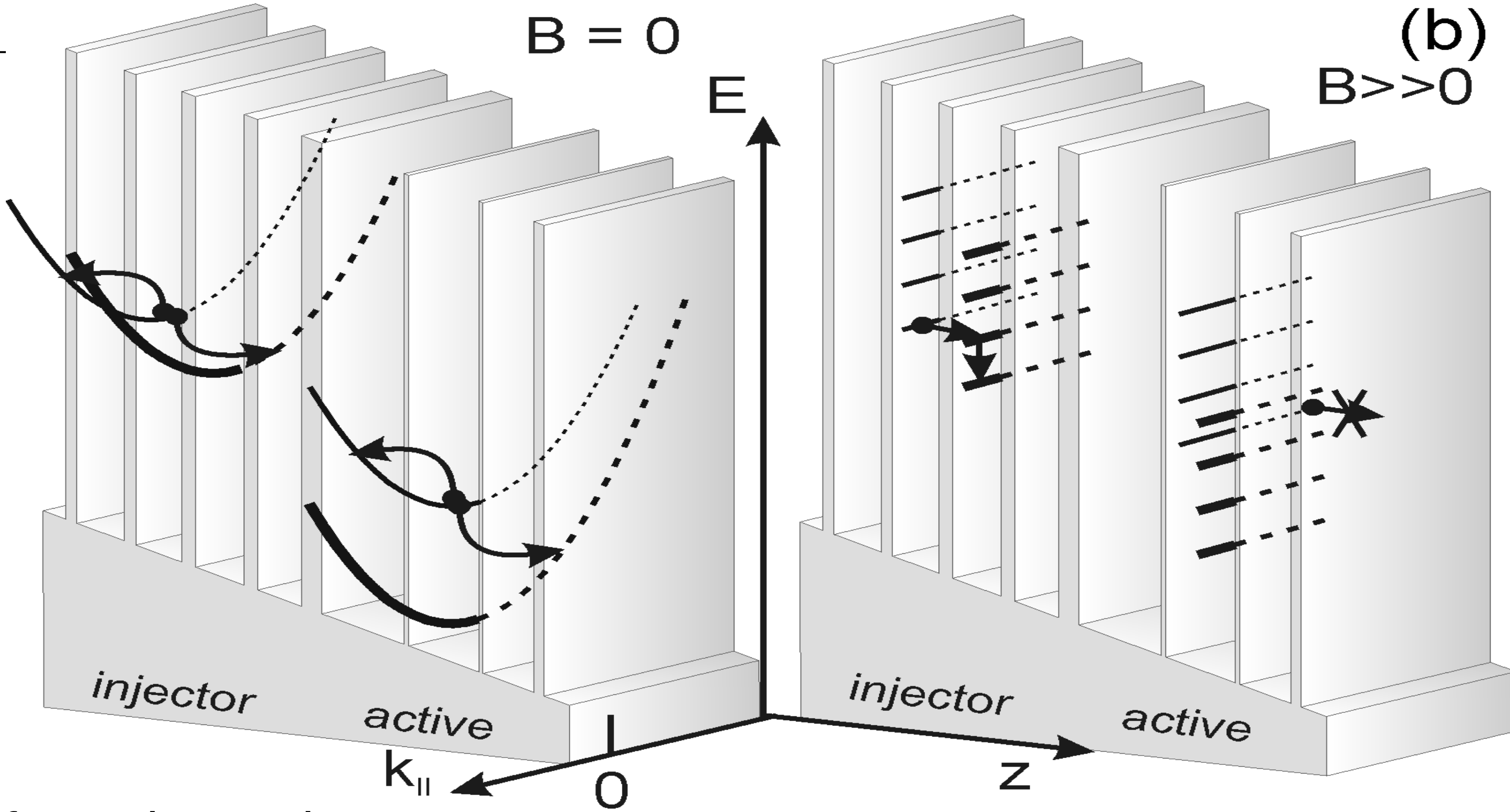
Landau quantization in plane

$$E_{j,N} = E_j^0 + \left(N + \tfrac{1}{2}\right)\hbar\omega_c$$

$$\omega_c = eB/m^*$$

(intersubband (z) motion and in-plane motion decoupled) complete quantization

Landau quantization



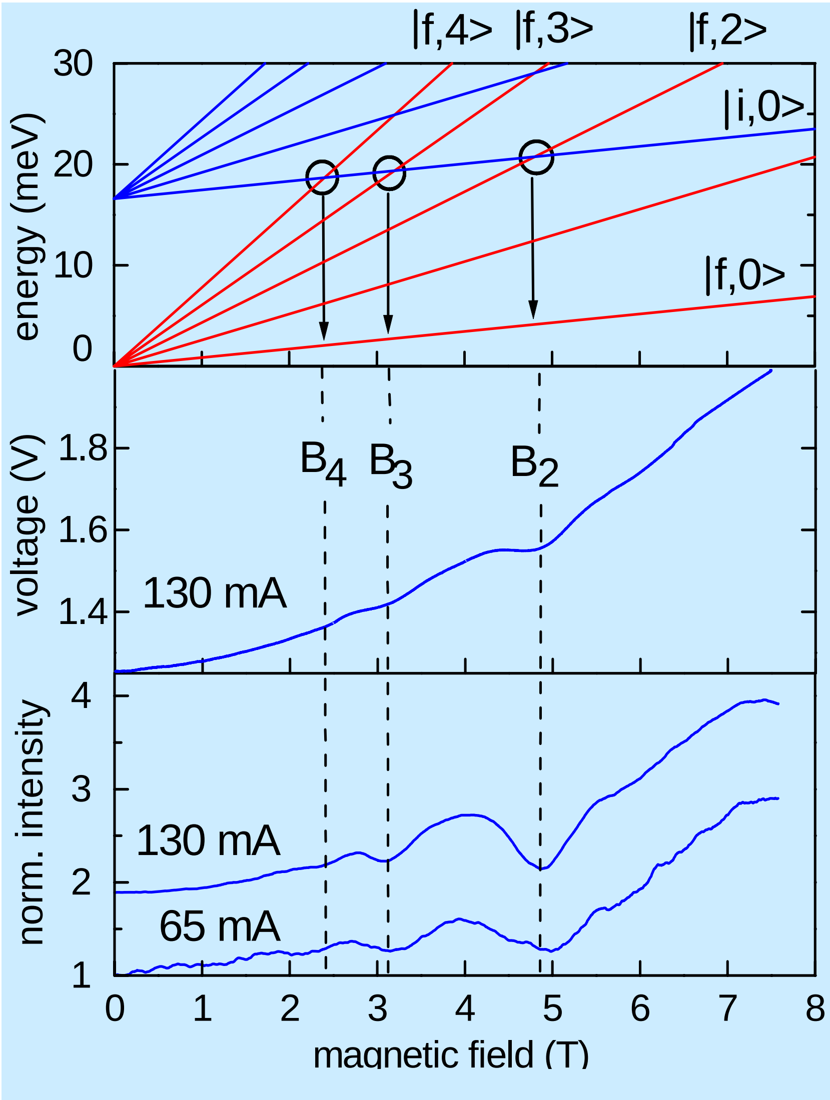
- for active region we want:

$$\frac{\hbar eB}{m^*}N \neq \Delta E_{laser}$$

- for injector we want:

$$\frac{\hbar eB}{m^*}M = \Delta E_{injector}$$

magneto-intersubband oscillations



Ulrich et al., Appl. Phys. Lett. 76, 19 (2000)

opening of a non-radiative channel if:

$$E_i^0 - E_f^0 = \frac{\hbar e B_N}{m^*} N$$

N (minima)	B_N
2	4.9
3	3.2
4	2.2

$$E_i^0 - E_f^0 = 16.6\, meV$$

comparable to measured emission photon energy:

$$E_i^0 - E_f^0 = 17.3\, meV$$

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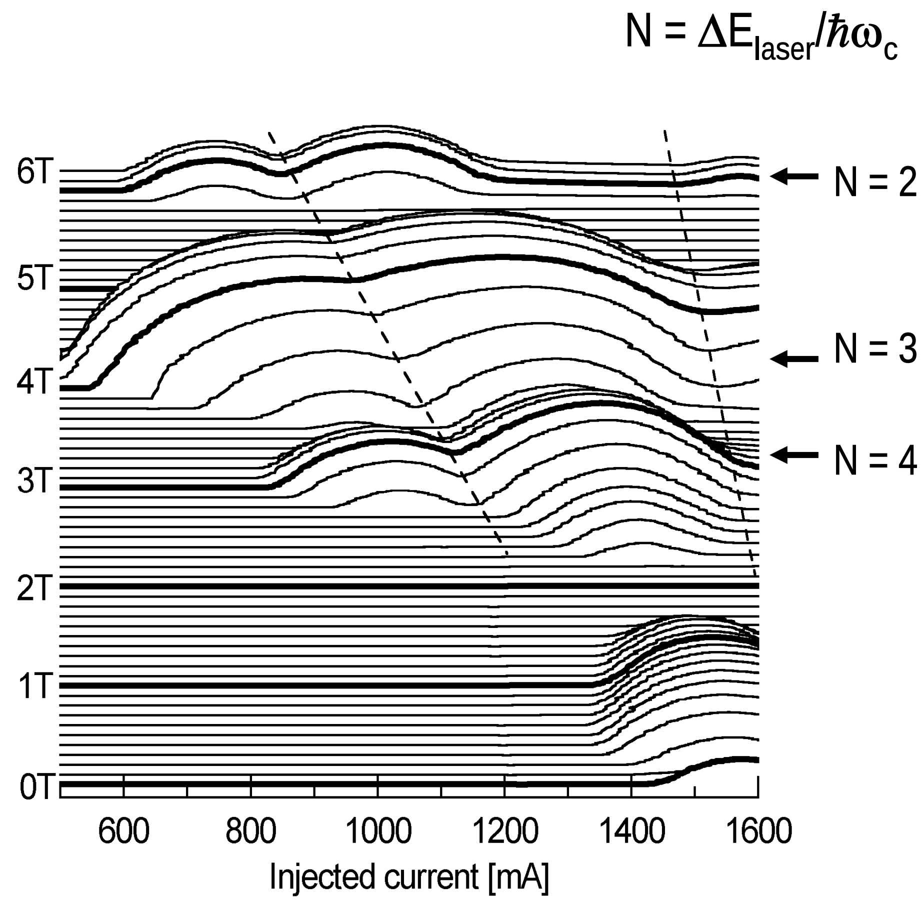
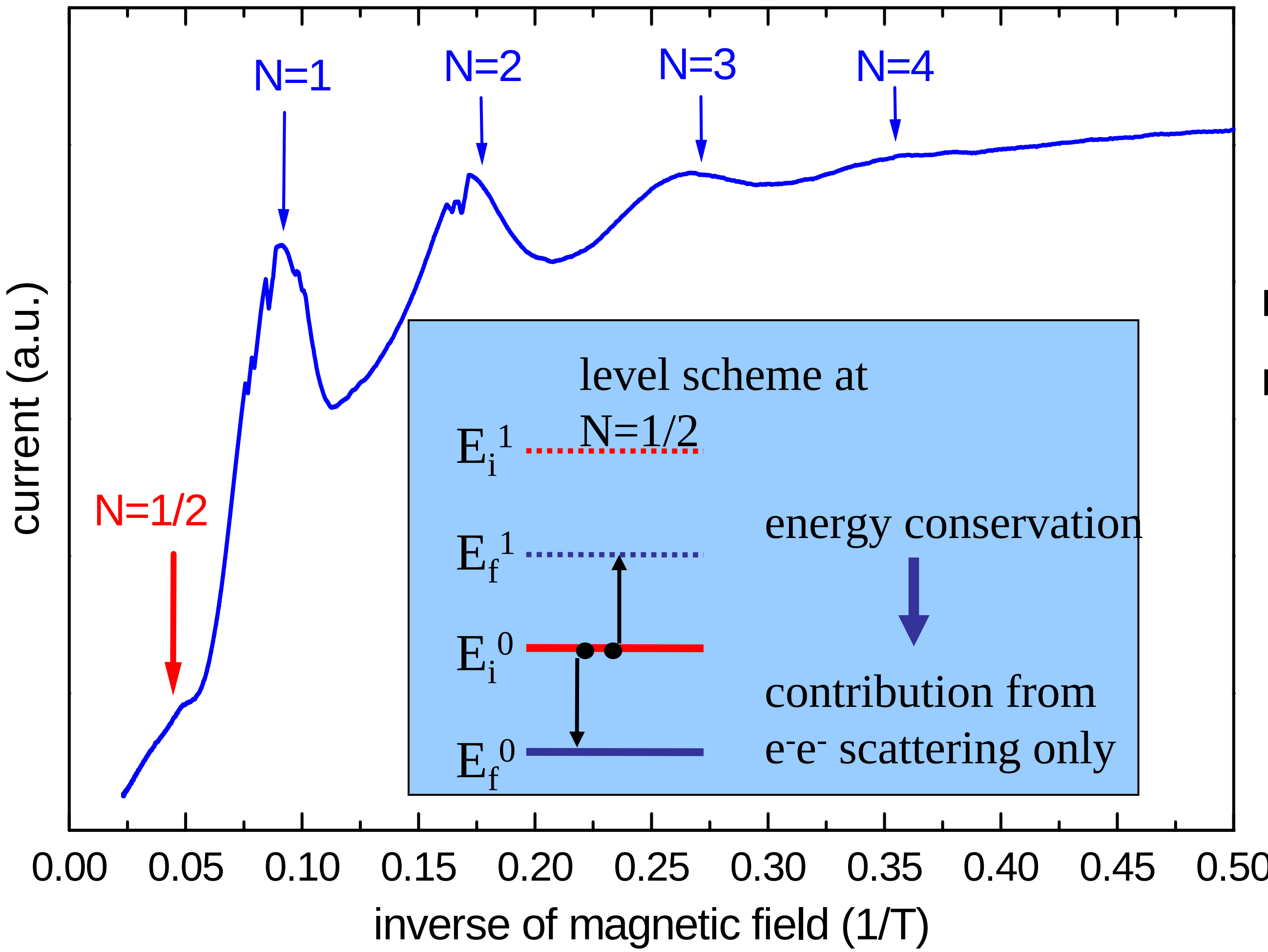
Laser emission versus current and magnetic field

V. Tamosiunas et al., Appl. Phys. Lett. 83, 3873 (2003).

- **Oscillations of the emission intensity**
- **Intensity minima:**
  Are observed for integer N , due to increased non-radiative relaxation in an active region
- **A reduction of the threshold current**
  From 1.35A at 0T…
  … to 0.5A at 4.2T
- **An increase of the emission intensity**
  Maximum at 4.2T
  More than 4 times when compared to 0T



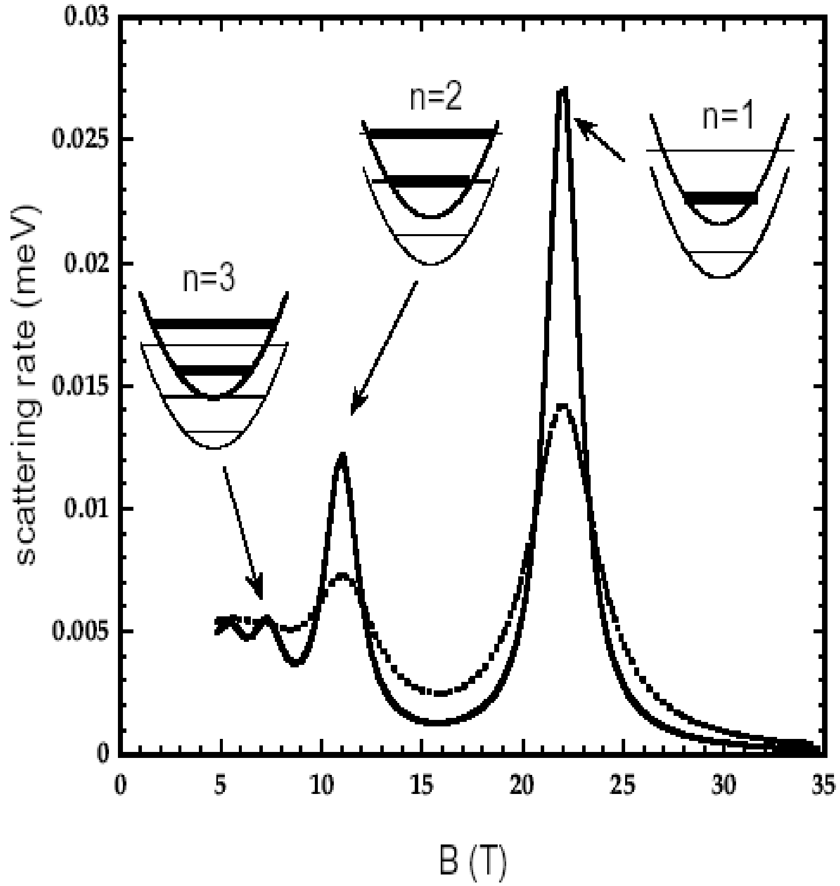
high magnetic field transport



Kempa et al., Phys. Rev. Lett. 88, 226803(2002).

- **half integer peaks are indication for e-e scattering mechanism**

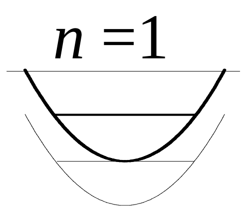
Non-resonant intersubband electron-electron scattering



Theory shows that el-el scattering rate peaks for ALL n (odd and even)

Sample: TU Vienna
Measurements: Boston College (M. Naughton's group) and in Vienna

Experimental results



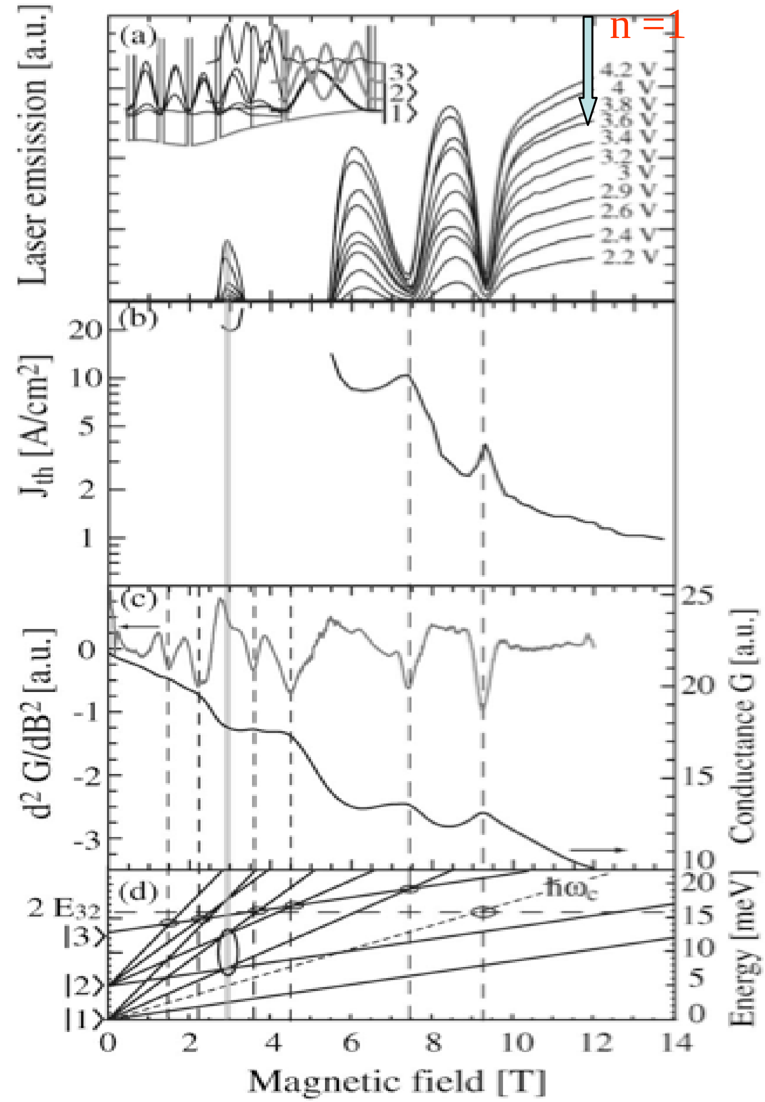
$$\hbar \omega_C = \frac{2\Delta}{n} \qquad n = 1, 2, 3, \ldots$$

G. Scalari et al. Phys. Rev. Letters, 93, 237403, (2004).

THz Cascade Laser

Fully confirmed the theory and experimental result of

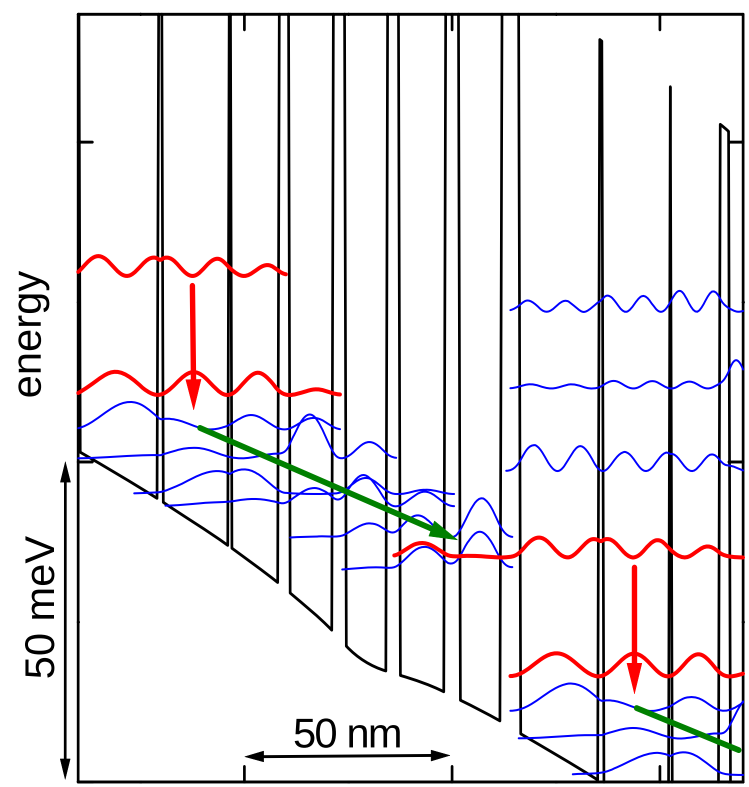
K. Kempa et al. Phys. Rev. Letters, 88, 226803, (2002).

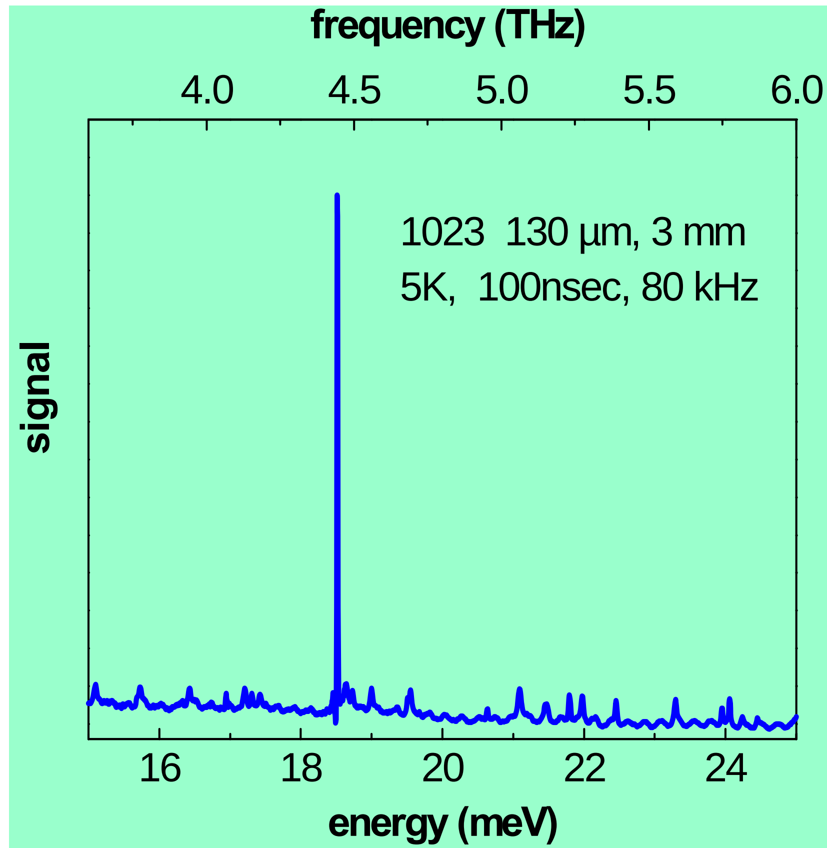


El-el scattering is a primary process in this structure

THZ QCL

Miniband design 15 meV

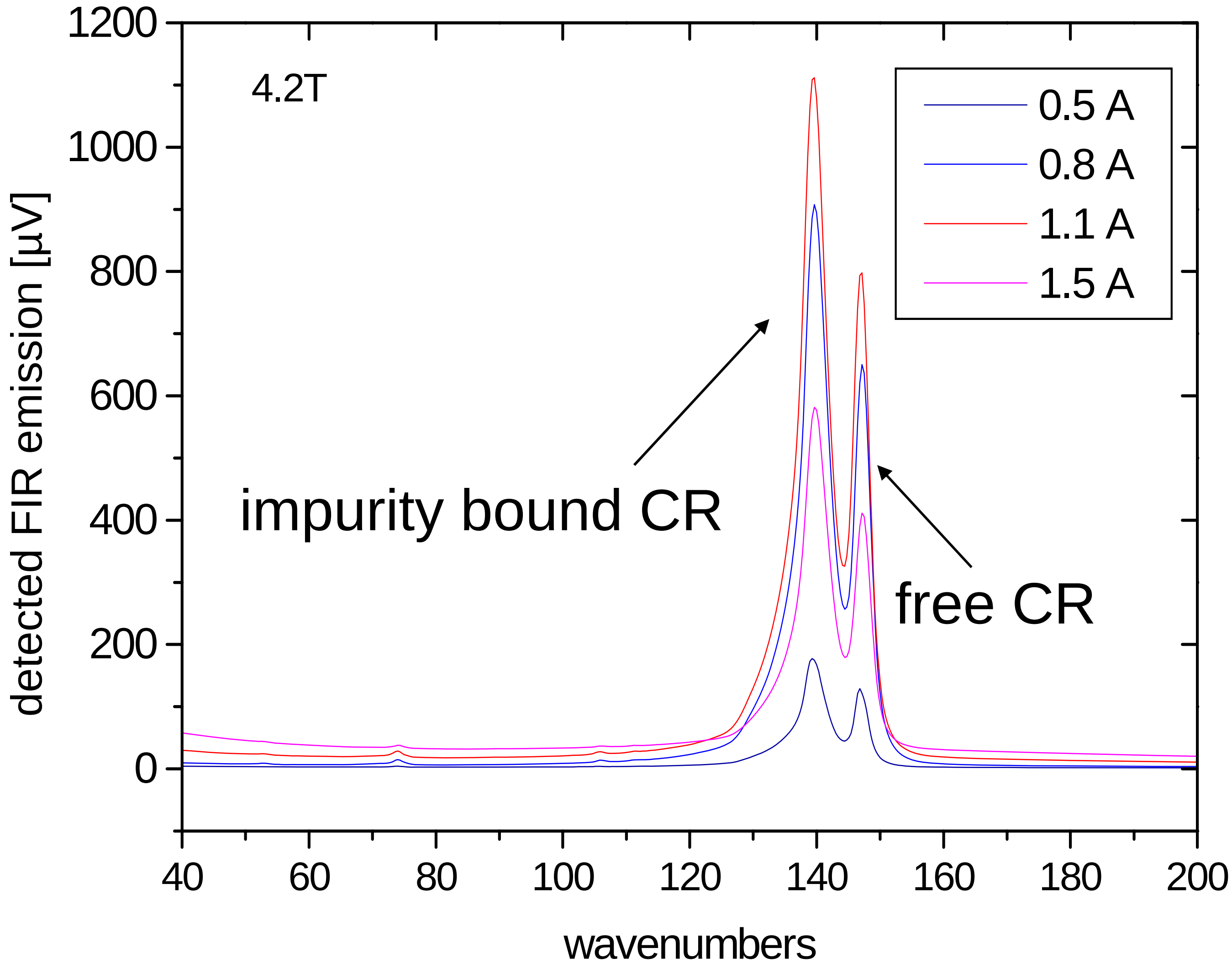




Köhler et al., Nature 417, 156(2002)

in collaboration with R. Colombelli, C. Gmachl, K. West,L. Pfeiffer, F. Cappaso, LUCENT

Application: InSb cyclotron resonance spectra



Conclusions for QCL work

- The intensity enhancement and the extreme threshold current reduction with magnetic field are attributed to:
  - the suppression of nonradiative Auger-intersubband transitions

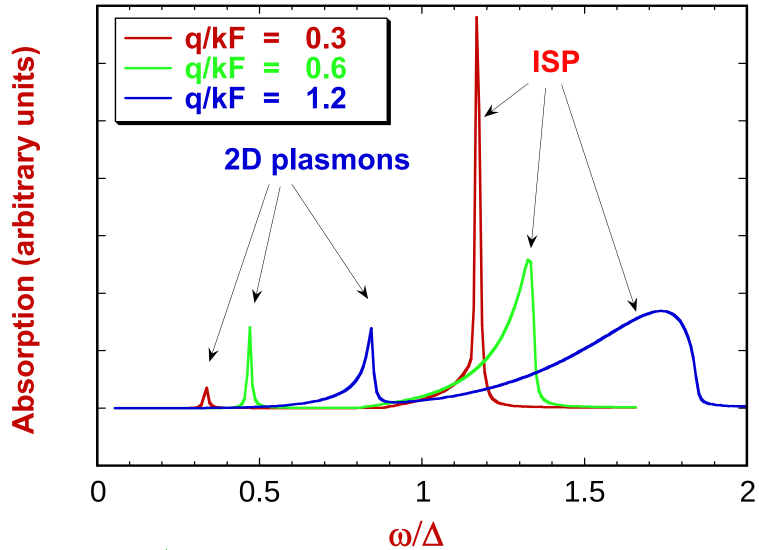
    by Landau-quantization of the in-plane electron motion,
  - the modulation of the injection rate via resonant inter-Landau-level transfer

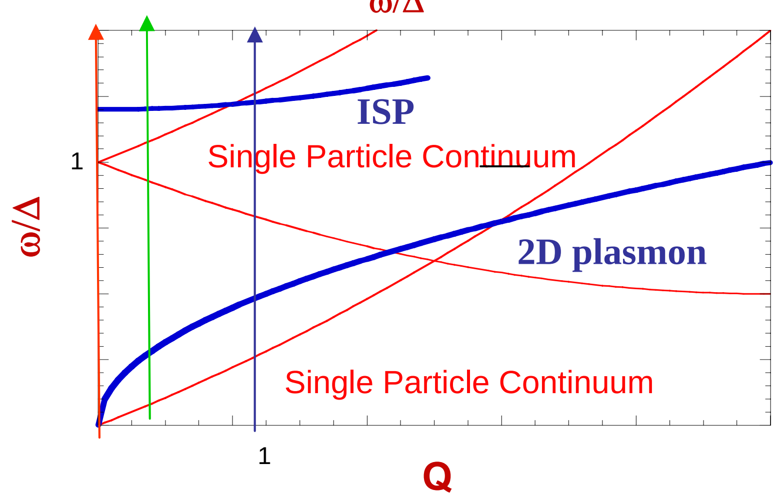
Intersubband Plasmons

- Theoretical aspects

- Experiments on a „three level system“ quantum well

Intersubband plasmons (ISP) in quantum wells
2 subband case

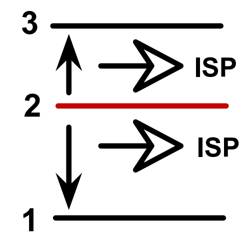


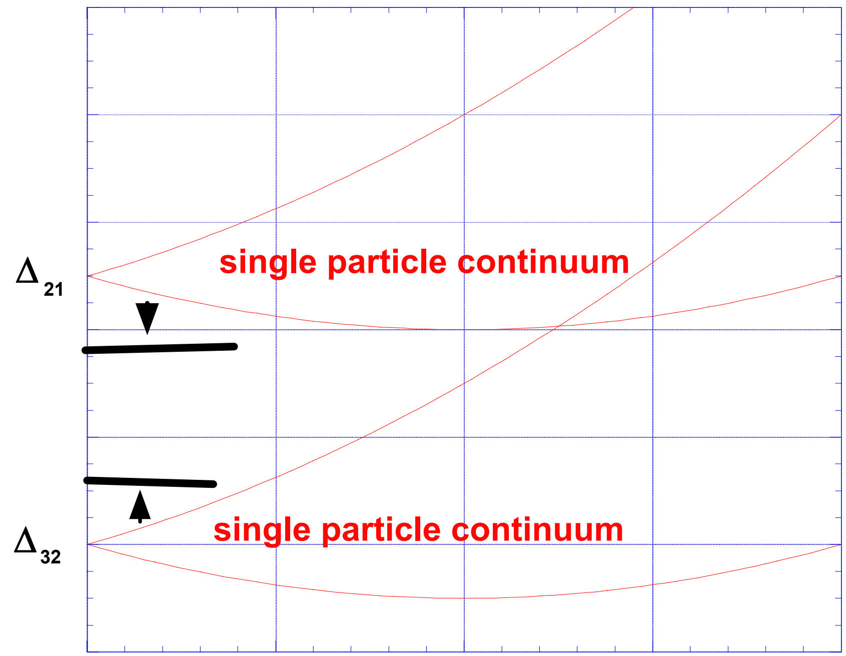


- ISP is a hybrid excitation
  It involves a single electron scattering between the subbands and a collective excitation (plasmon) of all electrons in the QW.
- ISP is *depolarization shifted* so that $\omega > \Delta$, for the "normal" subband occupation $n1 > n2$.
- For a reversed subband occupation ($n2 > n1$) the sign of the depolarization shift also reverses.

ISP in quantum wells
(3 subband case: 2nd filled)

- There are now two ISP, one depolarization shifted downwards and the other upwards, from the corresponding inter-subband separations.
- By reducing Δ_{21}-Δ_{32} and/or increasing electron density on subband 2 we can cause the two ISP to cross.

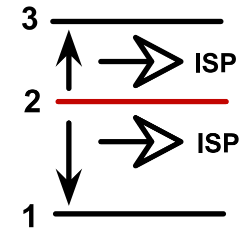


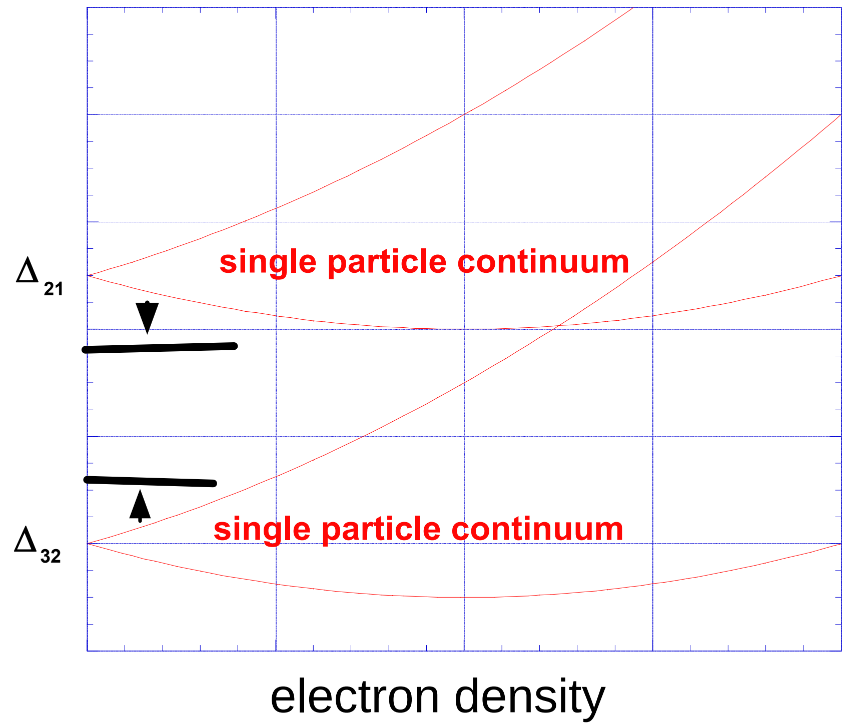


ISP in quantum wells
(3 subband case: 2nd filled)

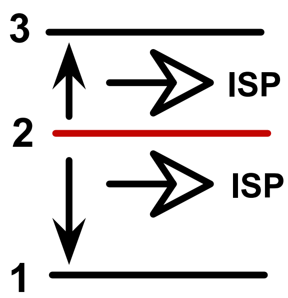
- The two ISP modes attractively cross.
- Pair of ISP modes forms, one unstable
- ($\omega'' > 0$): thus the candidate for stimulated emission.
- Since formation of each ISP pair involves transfer of two electrons out of suband 2, this process can be also viewed as a resonant electron-electron scattering.
- The rate of this process is

$$\gamma = \omega''.$$



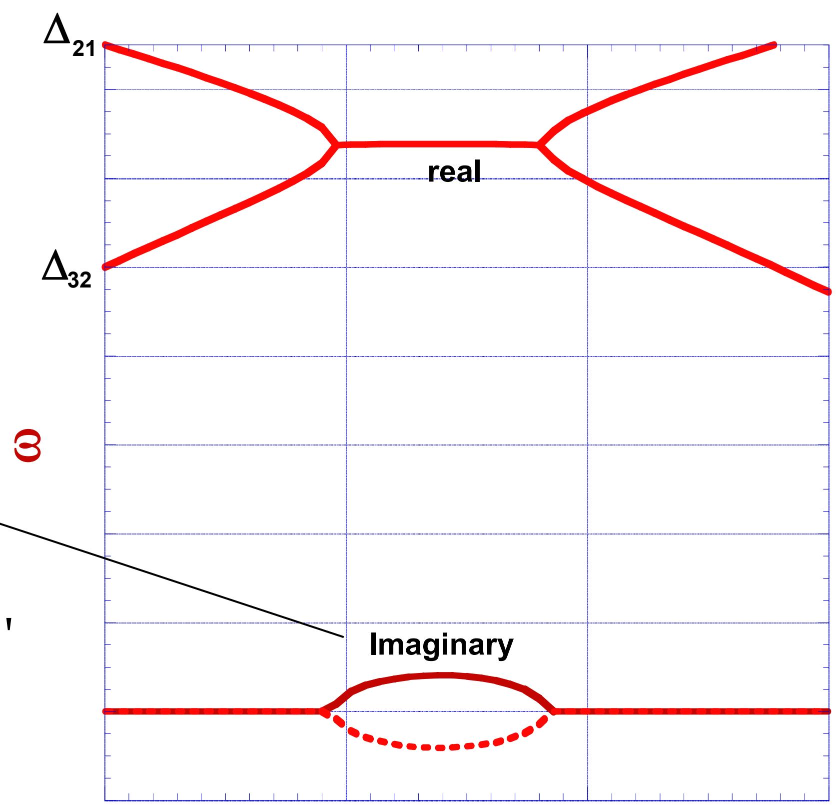


Stimulated ISP emission as resonant electron-electron scattering



$$\gamma = \mathrm{Im}(\omega) = 2(f_2 - f_1)(f_3 - f_2)\,|G_{12,23}|$$

$$G_{12,23} = \int \psi_1(r)\psi_2(r)\frac{1}{|r-r'|}\psi_2(r')\psi_3(r')\,dr\,dr'$$



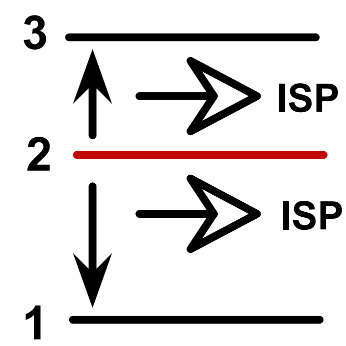
Electron density on subband 2

Analogue of plasma instabilities in gaseous plasmas

Realistic situation:

- Population inversion between subband 3 and subband 2 is possible by extracting carriers from subband 2 with a resonant RTD

- Subband 1 (populated by LO phonon emission) has a higher population than subband 2



Experimental results

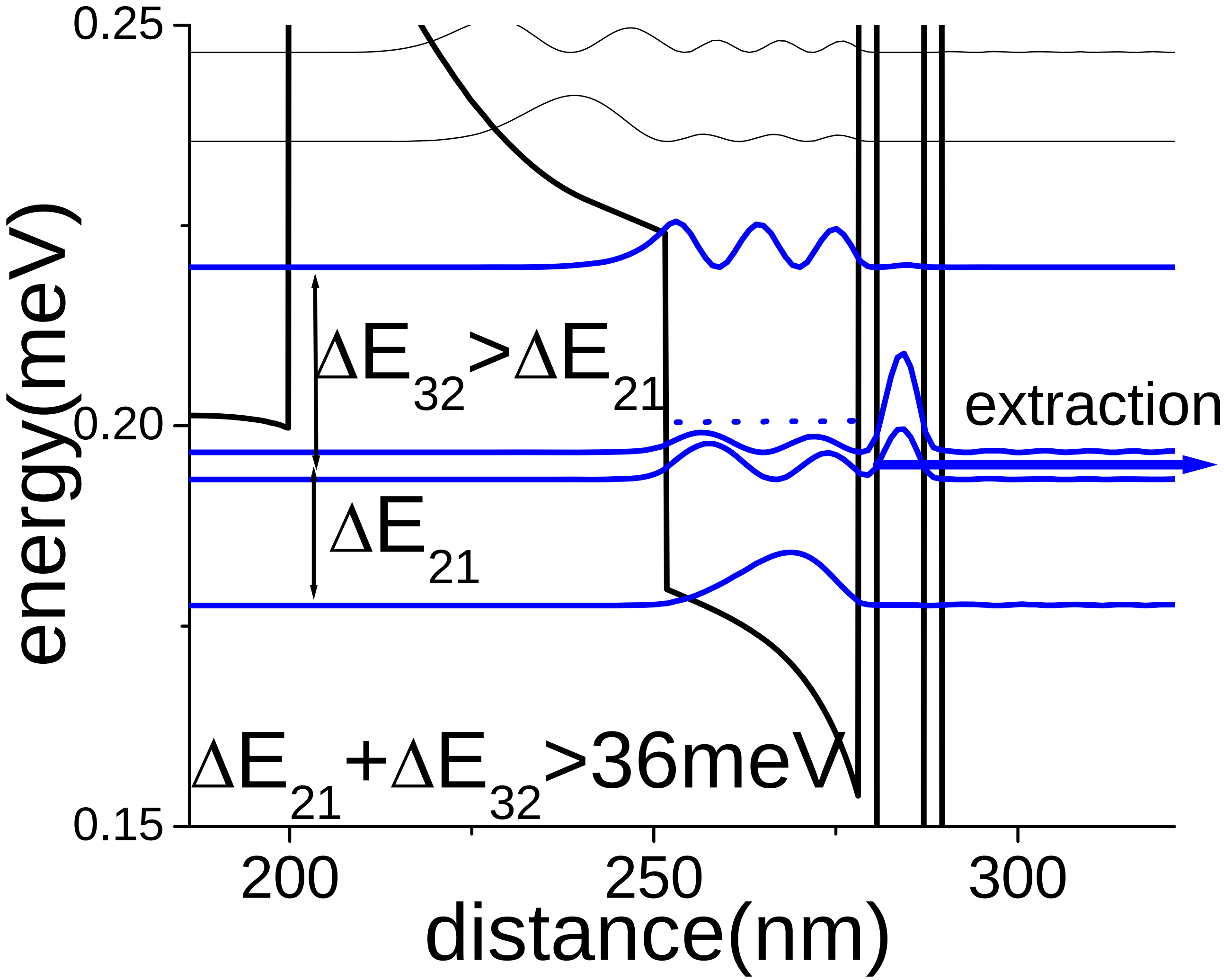
IV –curves

magnetic field effects

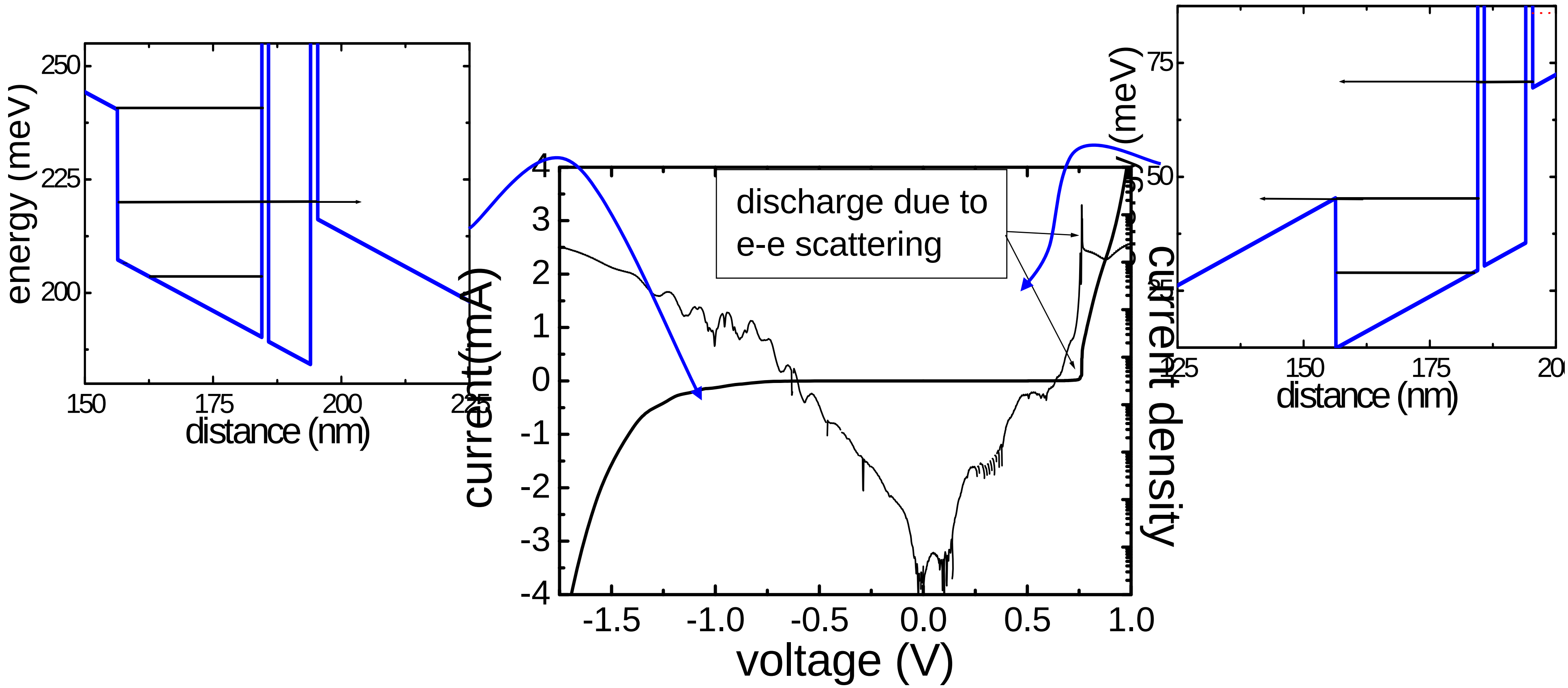
Emission spectra

with step scan Fourier spectrometer

Experimental three level system



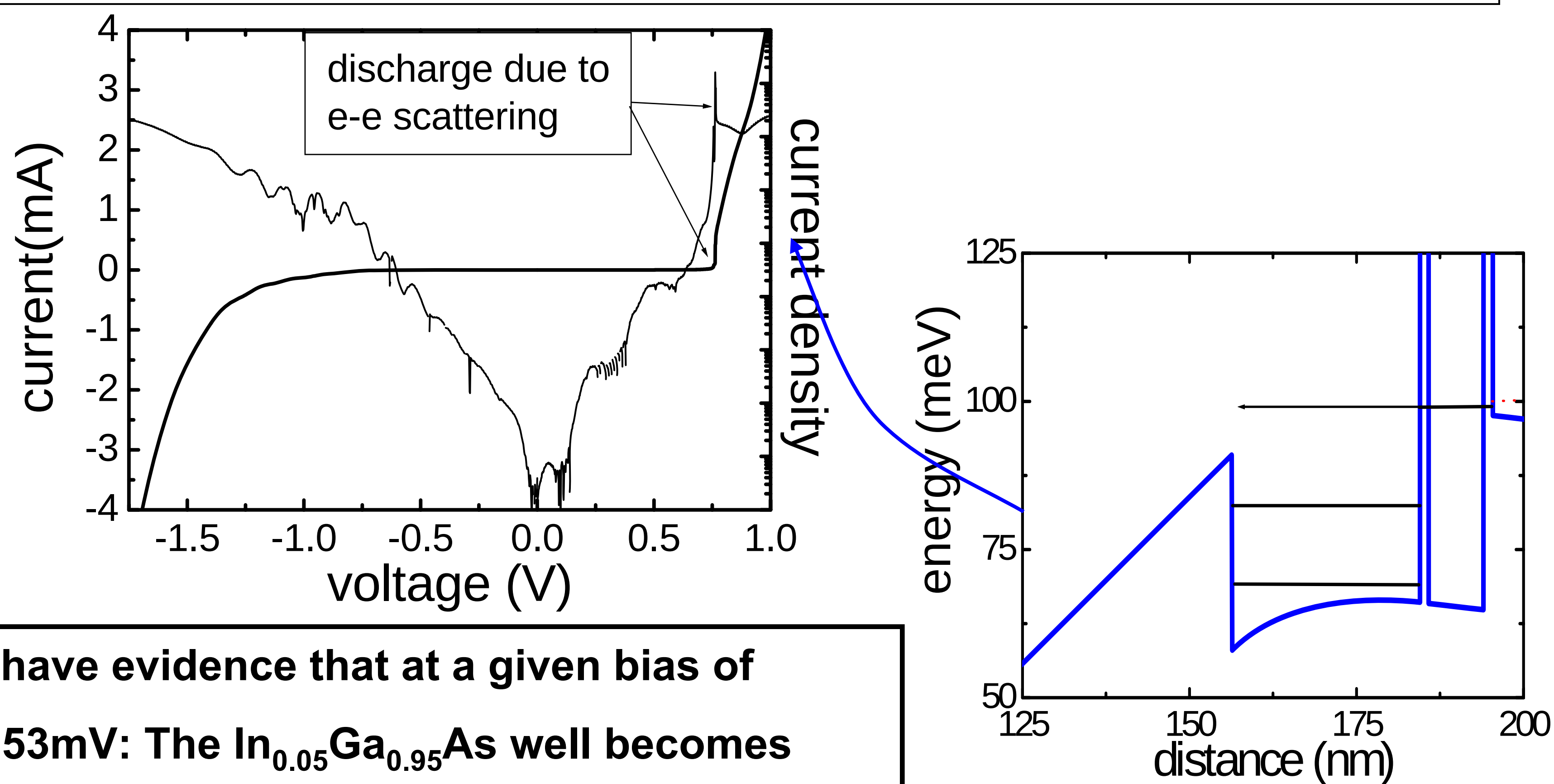
transport behaviour @ B=0T



Negative bias: RTD acts as extractor

Positive bias: RTD acts as injector

transport behaviour @ B=0T



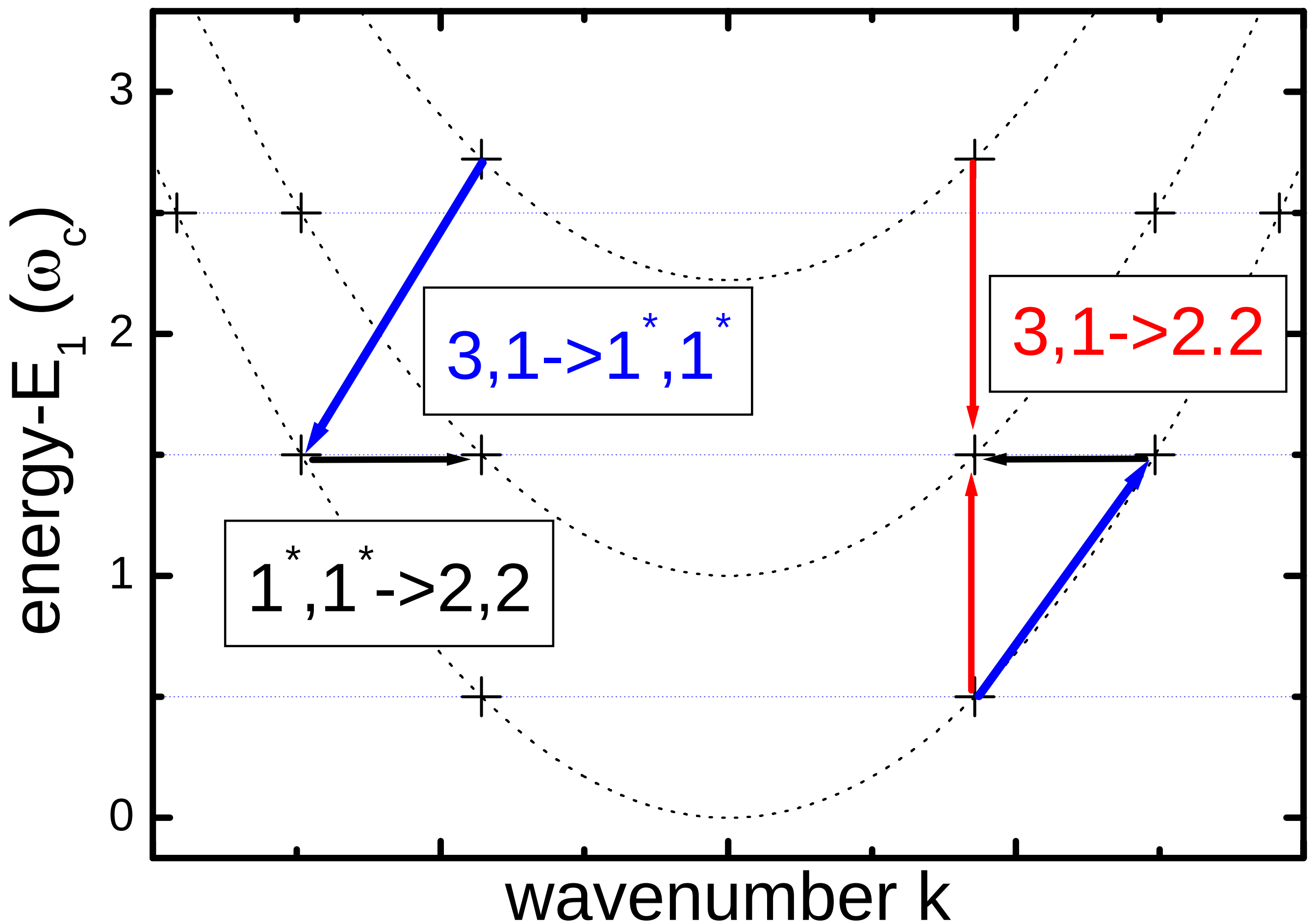
We have evidence that at a given bias of

V=753mV: The $In_{0.05}Ga_{0.95}As$ well becomes

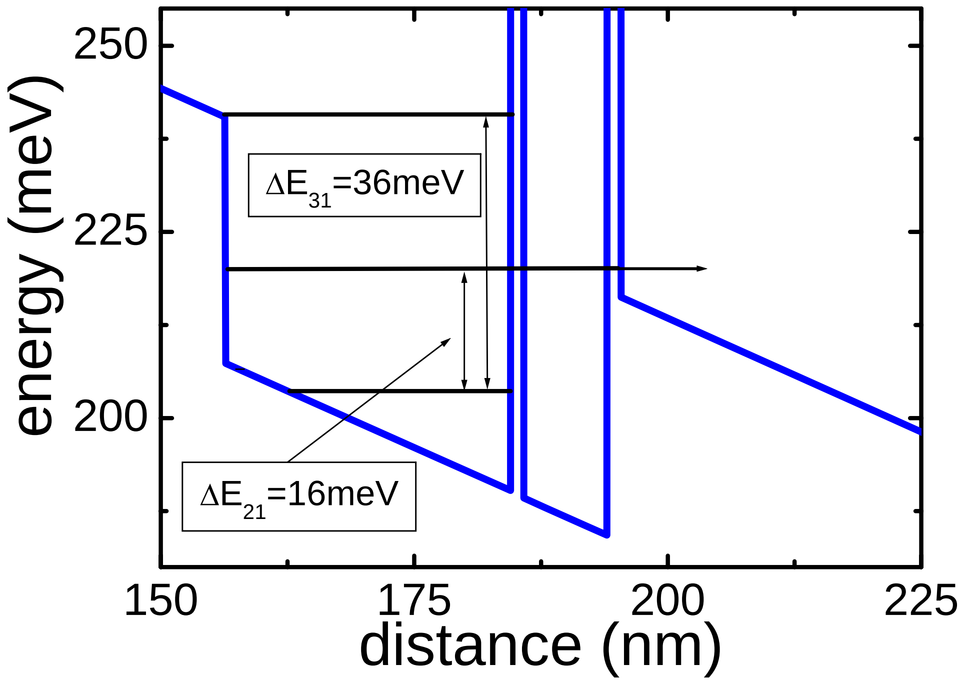
discharged due to e-e scattering

This is confirmed in magnetic field measurements

e-e scattering mechanisms



magnetic field current studies



Increasing B results in decreasing current
Additional possible scattering mechanism results in a current increase at B=4.5T and B=9T (ħωc=15.5meV) respectively B=5.5T and B=10.5T (ħωc=18meV) when the Laundau splitting is equal to the intersubband splitting

This indicates that e-e scattering (3,1✸2,2) is an important mechanism in this structure

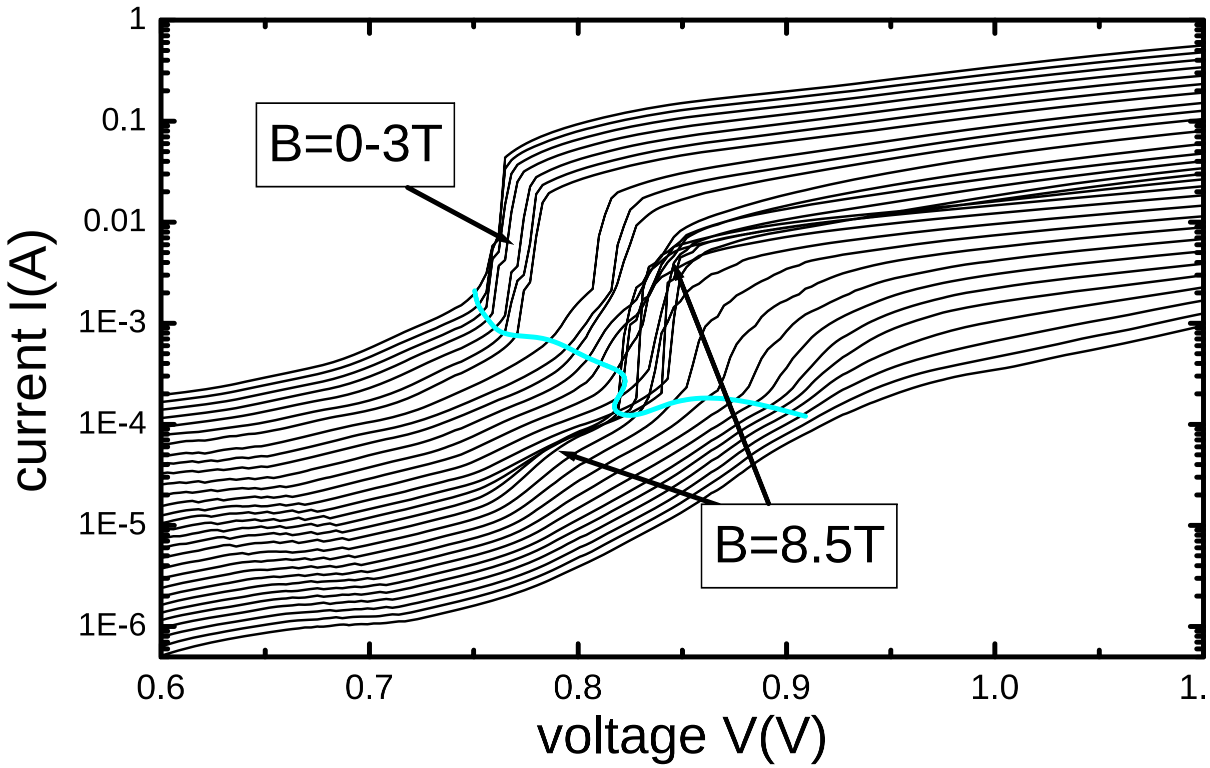
magnetic field (positive bias)

at current onset around V=752meV a strong influence of B observed:

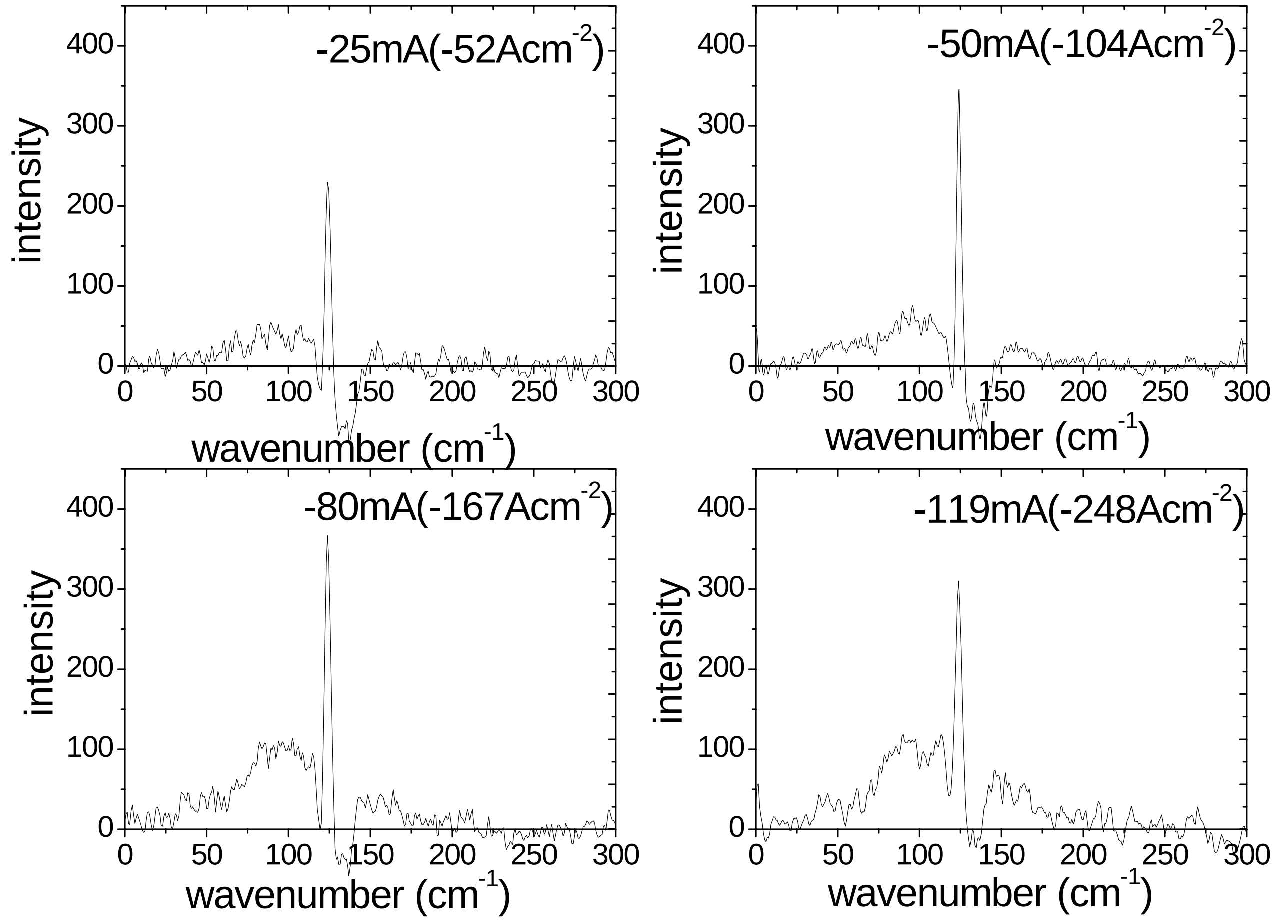
•The onset shifts to higher V with increasing B up to V=846meV (B=7T)

•Between B=7T and B=8.5T the onset shifts to lower voltages (V=820meV)

•Around B=8.5T a small peak occurs in the bias range between V=750meV and V=820meV, indicating filling of the second energy level without efficient extraction

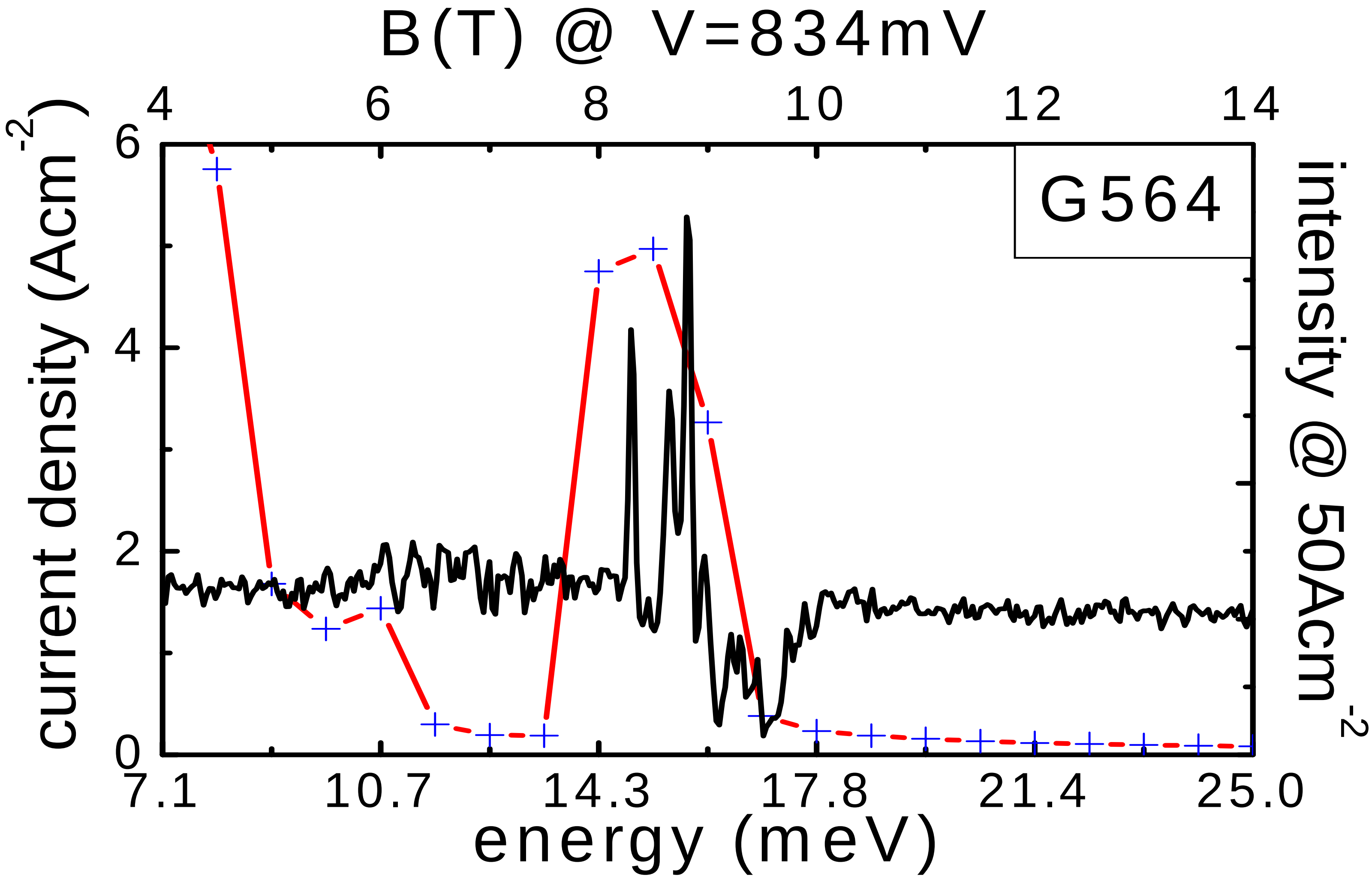


W2: Intersubband resonance: emission results



device area: A=5e-4cm^2

G564: spectral behaviour (ISP-resonance)



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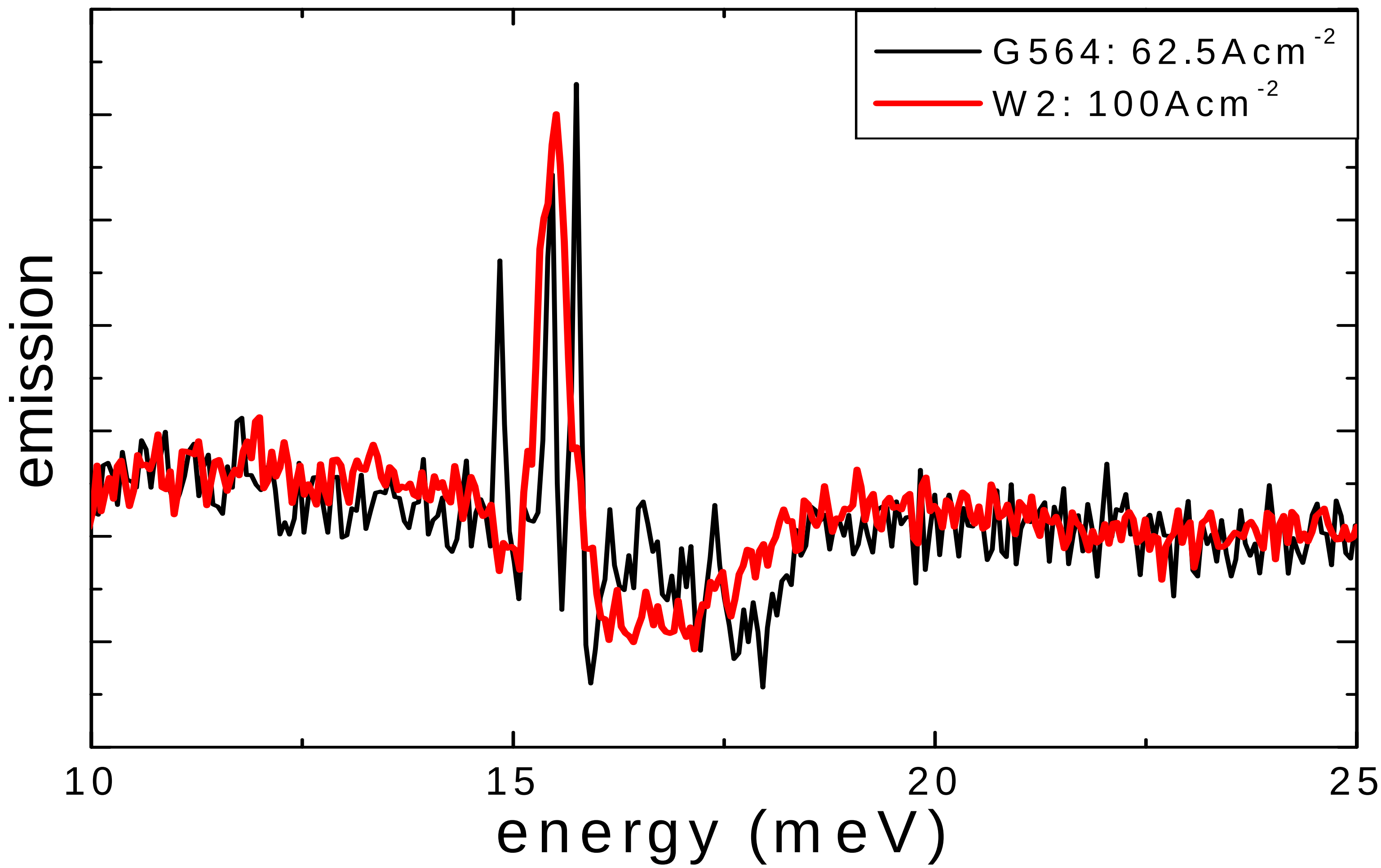
Comparison of emission results at ISP resonance

W2:30 cascades G564: 10cascades



Summary

- QCL intensity enhancement:
- extreme threshold current reduction with magnetic field

- ISP-Emission of THz radiation:
- signature of Plasma Instability
- Magnetis field studies confirm the resonant e-e-process
- The emission persisted up to 70K

- Goal is to realize a coherent THz source based on stimulated plasma oszillations
- Work on improved structures is planed