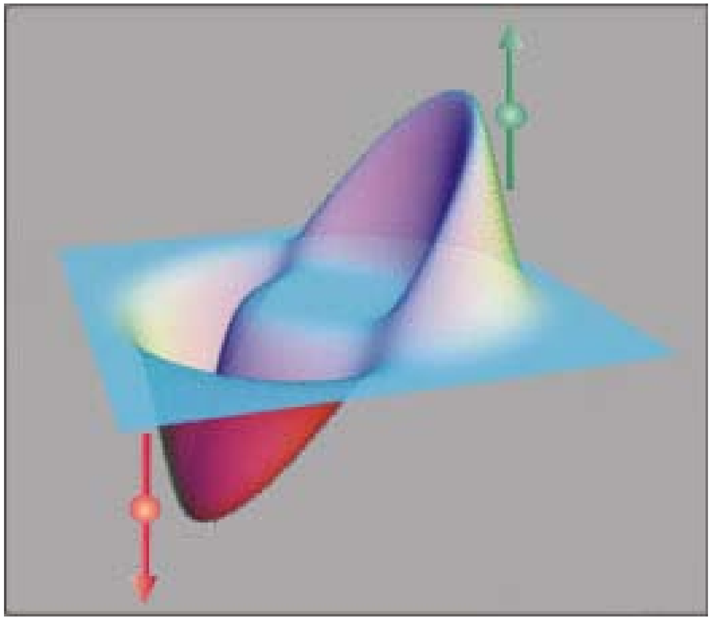
Coherent optical generation of ballistic spin currents

J.E. Sipe
Department of Physics
and
Institute for
Optical Sciences
University of Toronto



Spintronics
Wednesday,
22 March 2006

R.D.R. Bhat
Ali Najmaie
Fred Nastos
Ilya Rumyantsev
Eugene Sherman

H.M. van Driel
Yaser Kerachian
Norman Laman

University of Toronto

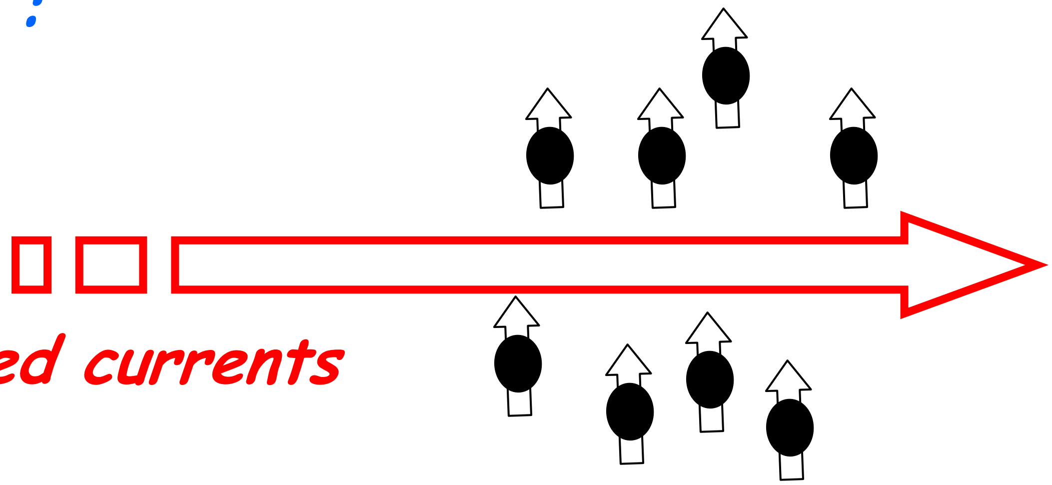
A.L. Smirl
Petr Nemec
Martin Stevens
Xinyu Pan
Hui Zhao

University of Iowa

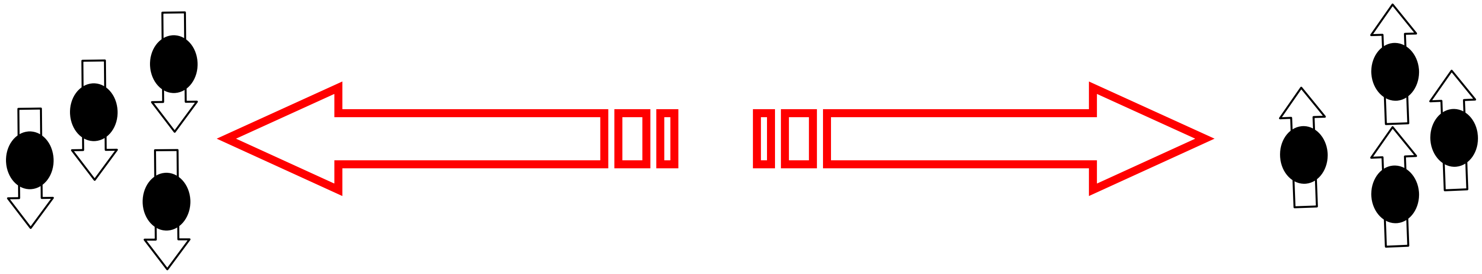
$$$

Natural Sciences and Engineering Research Council
Photonics Research Ontario
DARPA SpinS Program

"Take home message":



spin-polarized currents



pure spin currents

can be generated all-optically,
by a host of different schemes

These schemes are

ROBUST

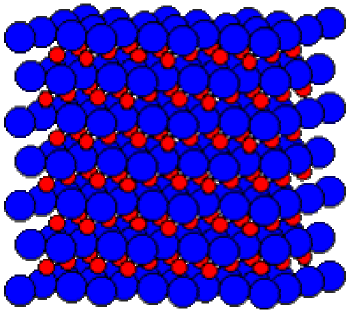
Conan the Barbarian

These schemes are

ROBUST

Conan the Barbarian

They only rely on:



The presence of the lattice

$$H_{SO} = -\frac{\hbar}{4m^2c^2}\vec{\sigma}\cdot\vec{p}\times(\nabla V)$$

Effects of spin-orbit coupling on band structures

Disadvantages:

Advantages:

Disadvantages:

somewhat "embarrassing" for a theorist:
not much more than Fermi's Golden Rule is required,

Advantages:

Disadvantages:

somewhat "embarrassing" for a theorist:
not much more than Fermi's Golden Rule is required,

...although there are interesting connections with
the theory of nonlinear optics and the theory
of linear and nonlinear magneto-optics

Advantages:

Disadvantages:

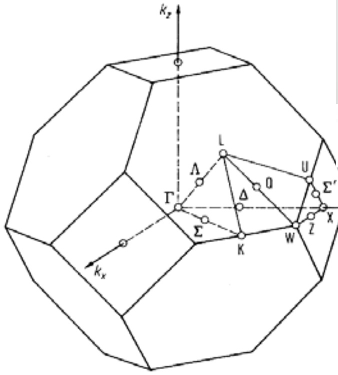
somewhat "embarrassing" for a theorist:
not much more than Fermi's Golden Rule is required,

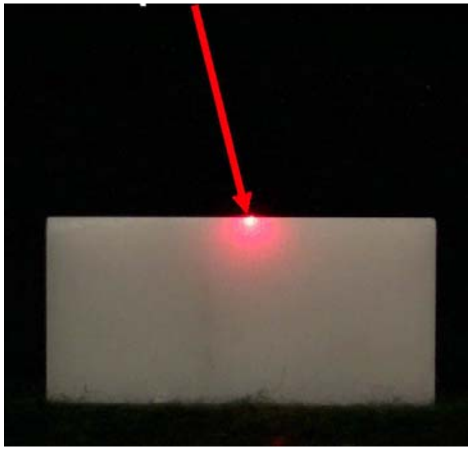
…although there are interesting connections with
the theory of nonlinear optics and the theory
of linear and nonlinear magneto-optics

Advantages:

can employ these schemes in the laboratory
to study more complicated many-particle
dynamics in condensed matter physics

"tweezers" in spin and reciprocal space....

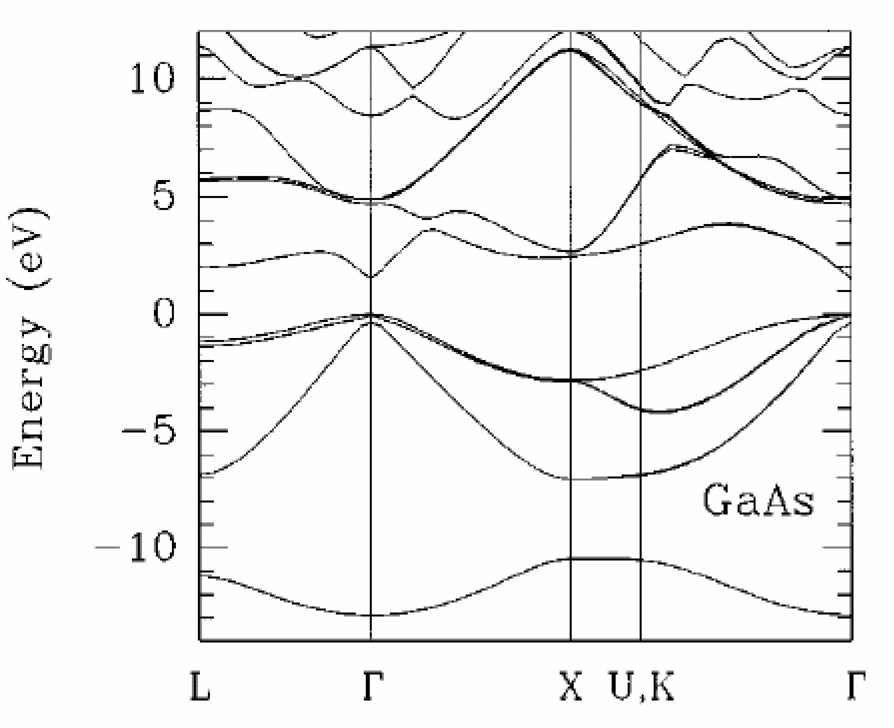




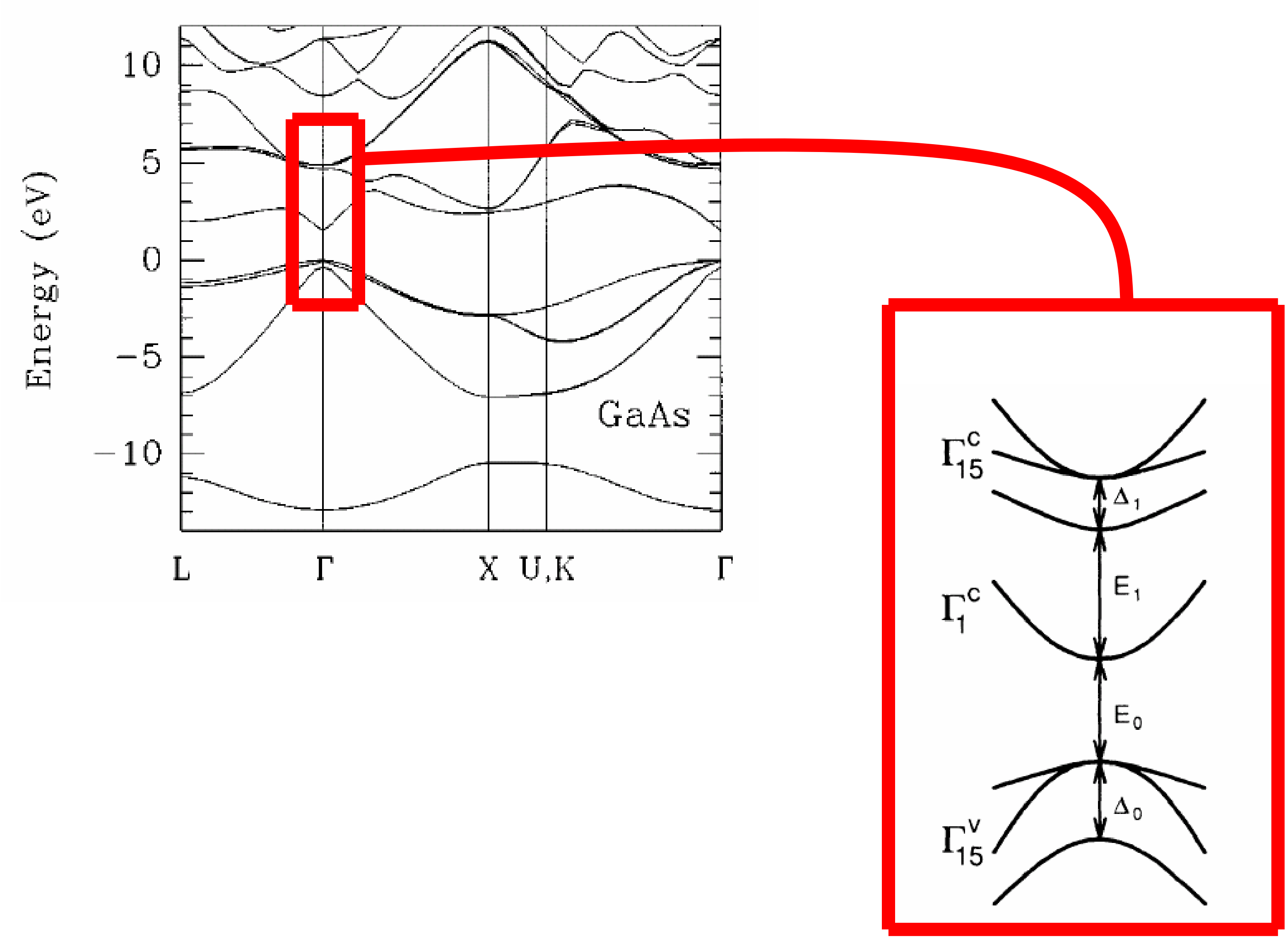
...and in real space

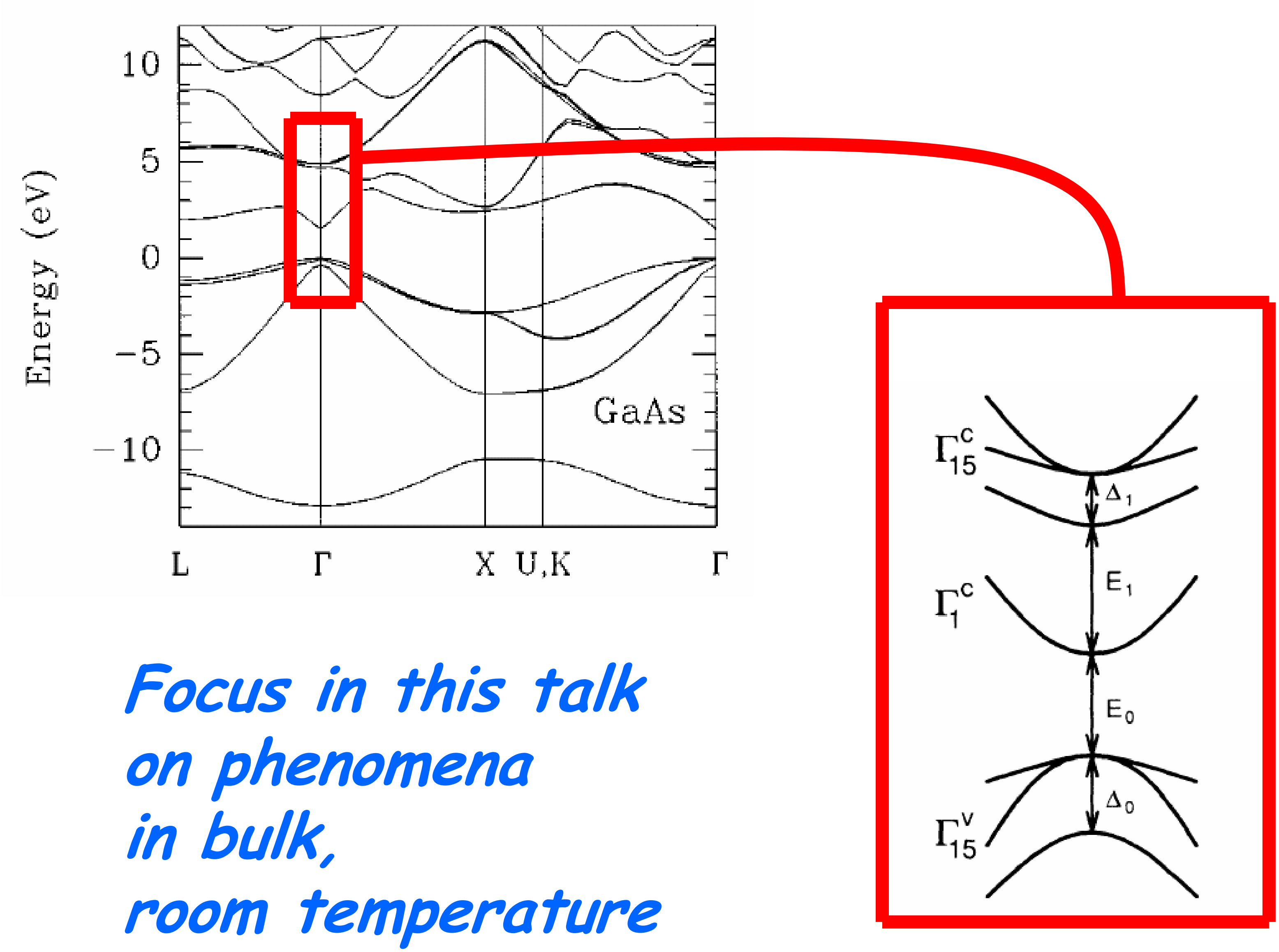
Outline:

- A quick review
  - optical orientation
  - coherent current control
- Two-colour processes
- One-colour processes
- Extensions and new schemes



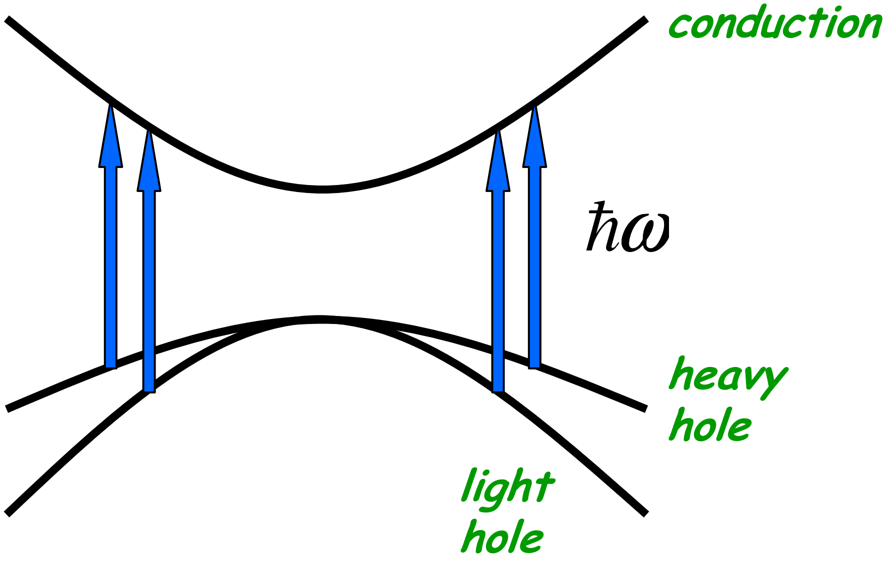
Energy (eV)
10
5
0
−5
−10
GaAs
L
Γ
X
U,K
Γ

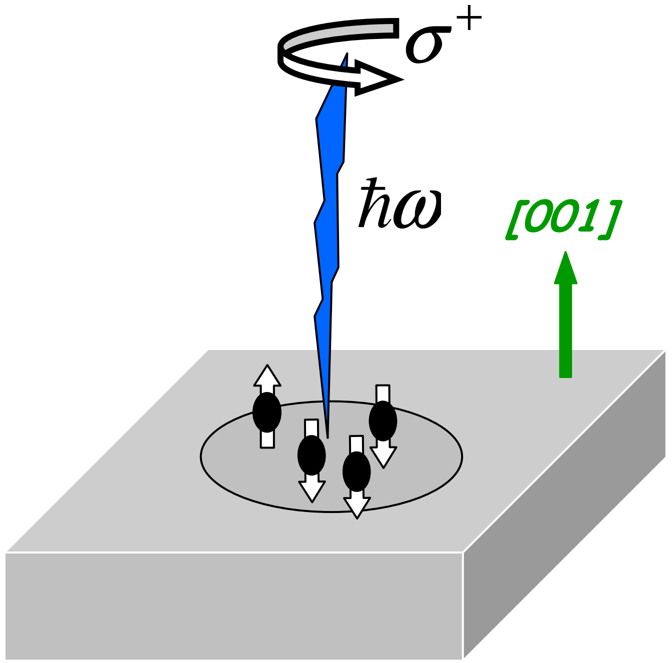

Energy (eV)
10
5
0
−5
−10
GaAs
L
Γ
X
U,K
Γ
Γ_{15}^{c}
Δ_1
E_1
Γ_1^{c}
E_0
Δ_0
Γ_{15}^{v}



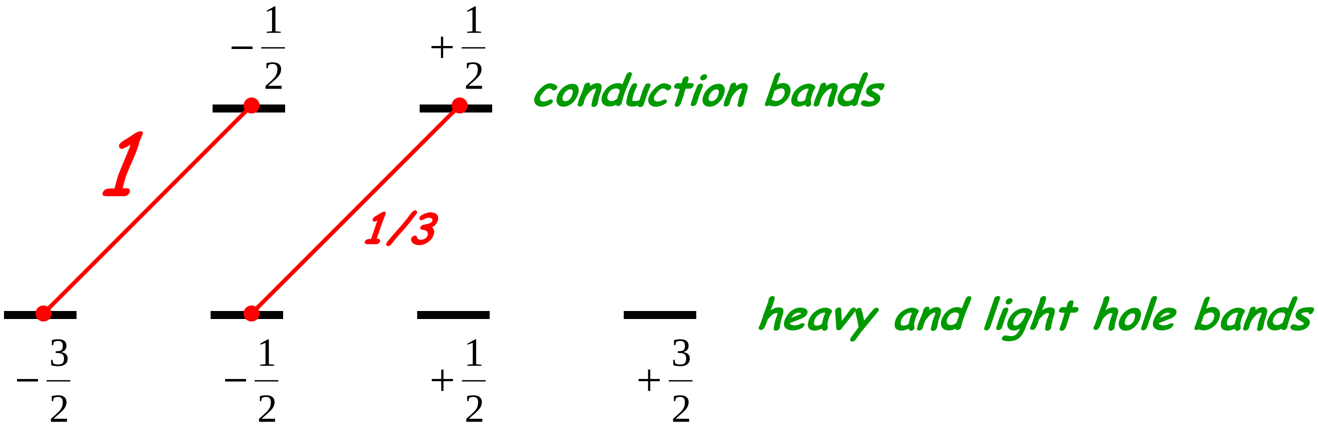
Focus in this talk
on phenomena
in bulk,
room temperature
samples

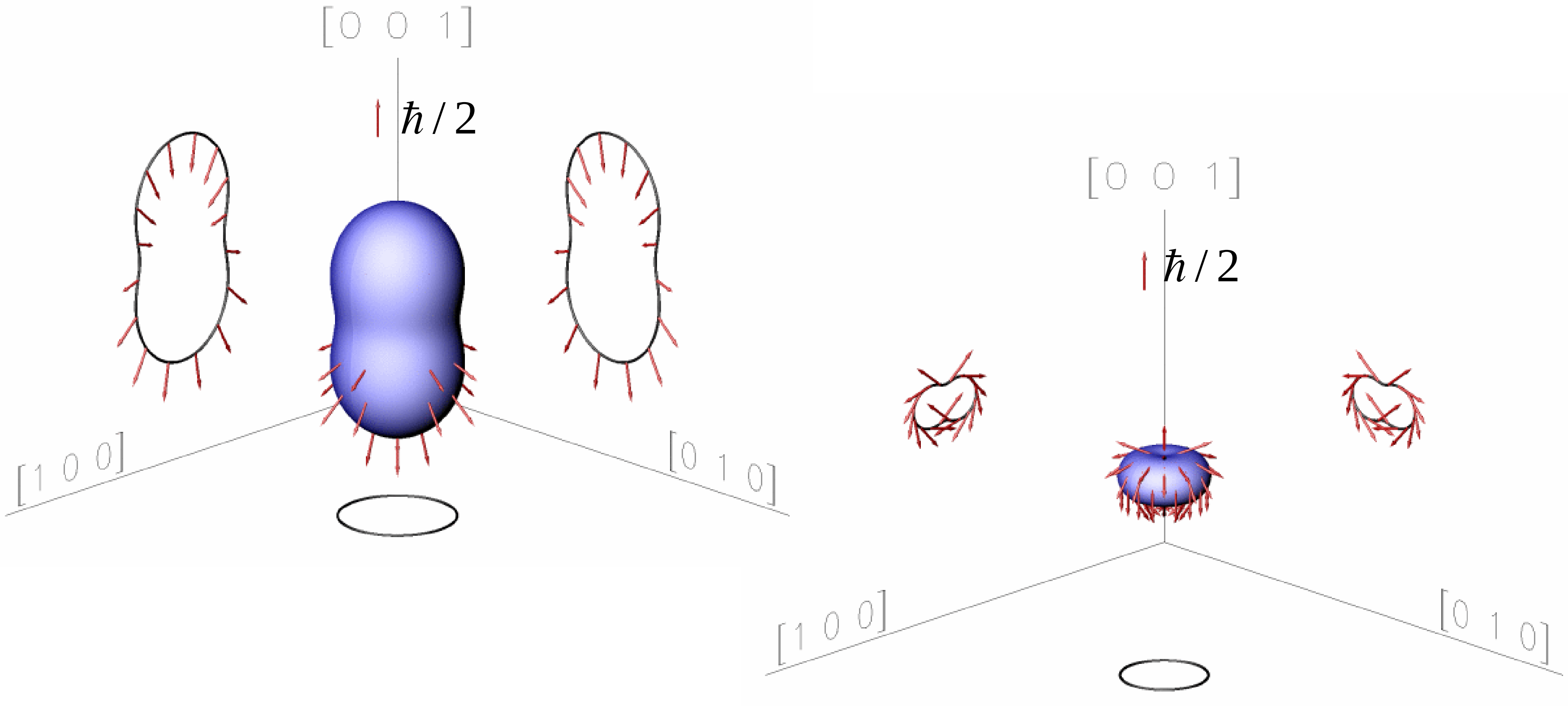
optical orientation





F. Meier and B.P. Zakharachenya, "Optical Orientation" (1984)

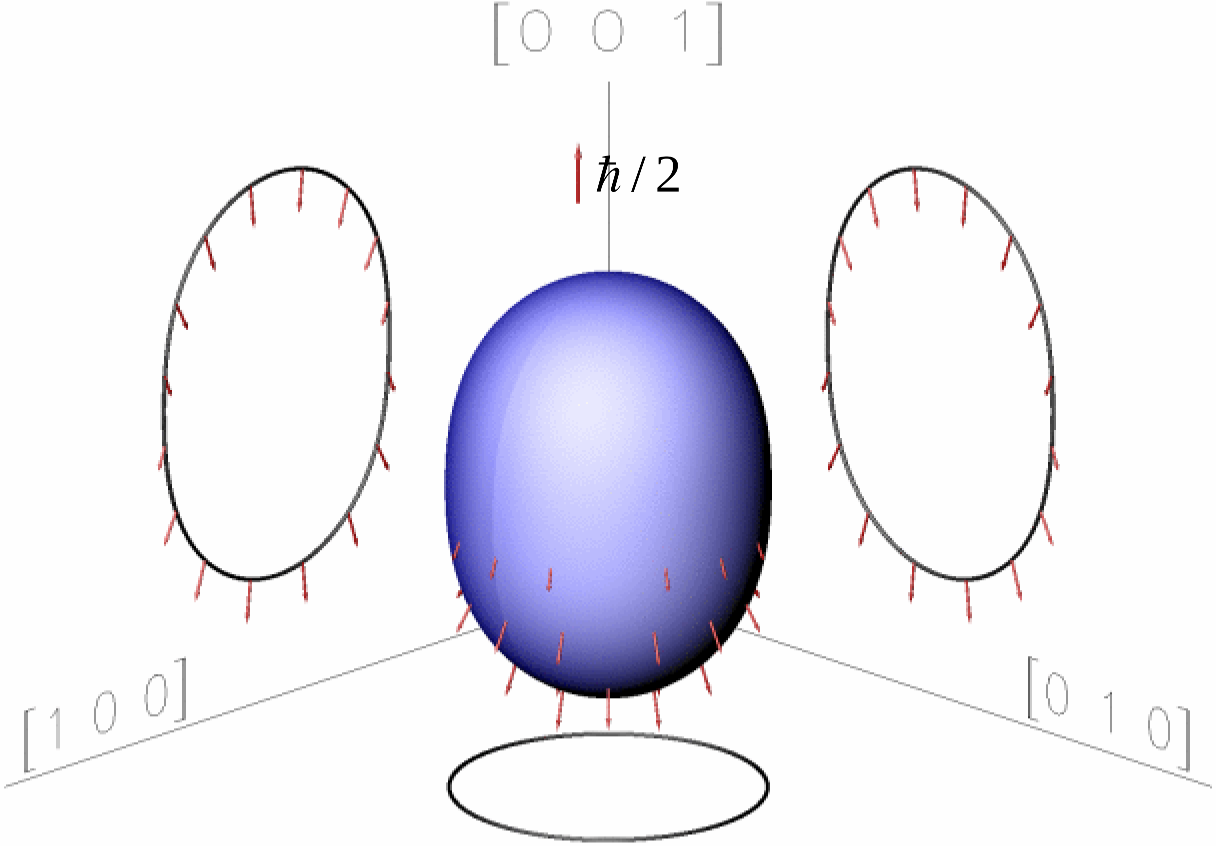




electrons from
heavy hole band

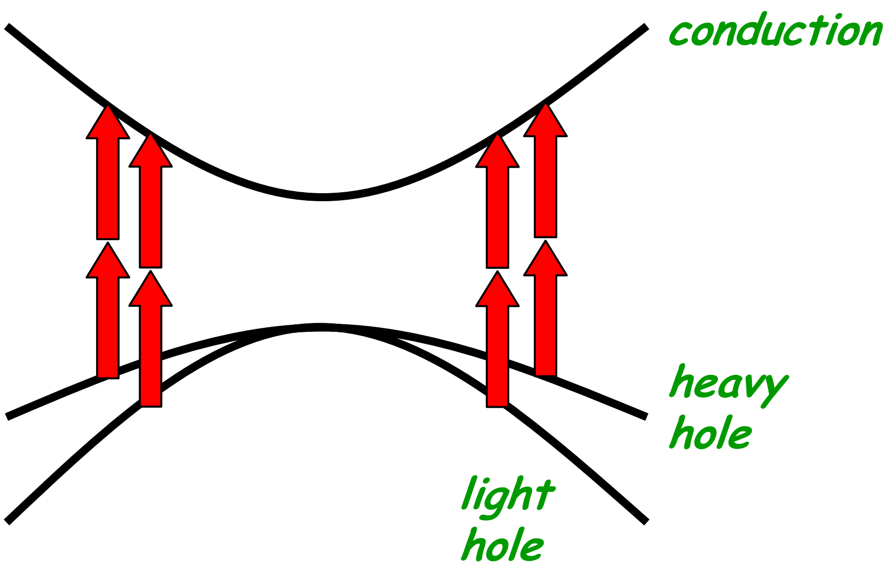
electrons from
light hole band

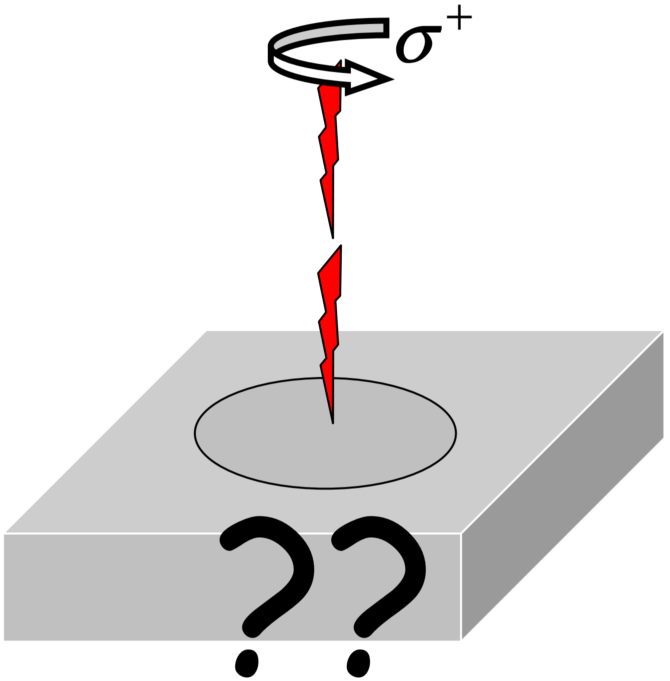
20 meV excess energy



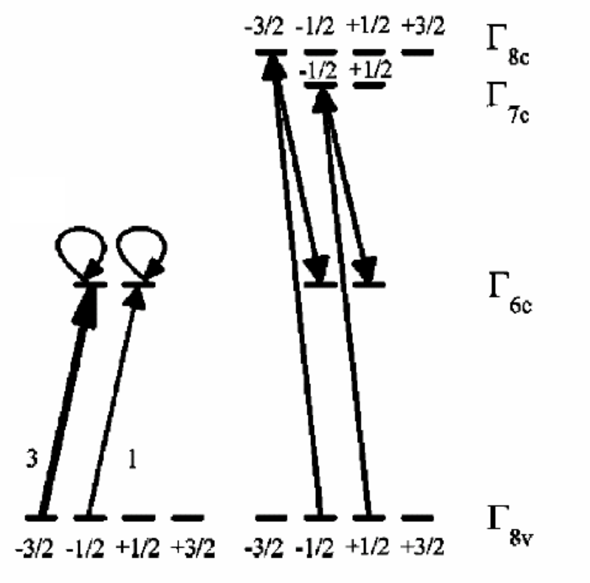
all electrons injected

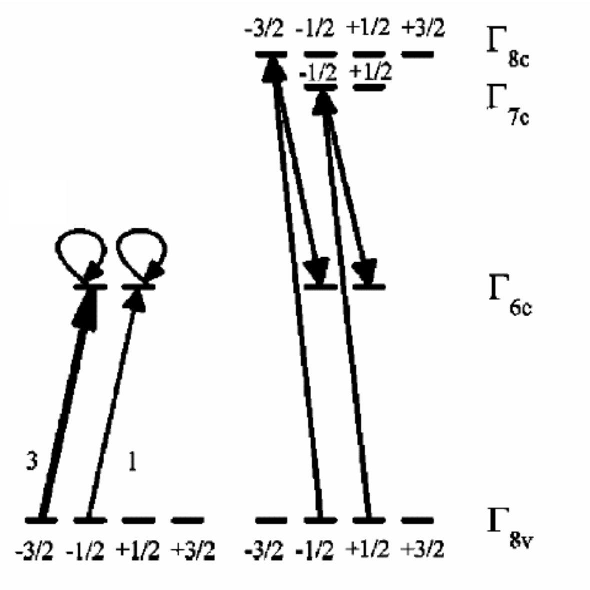
20 meV excess energy

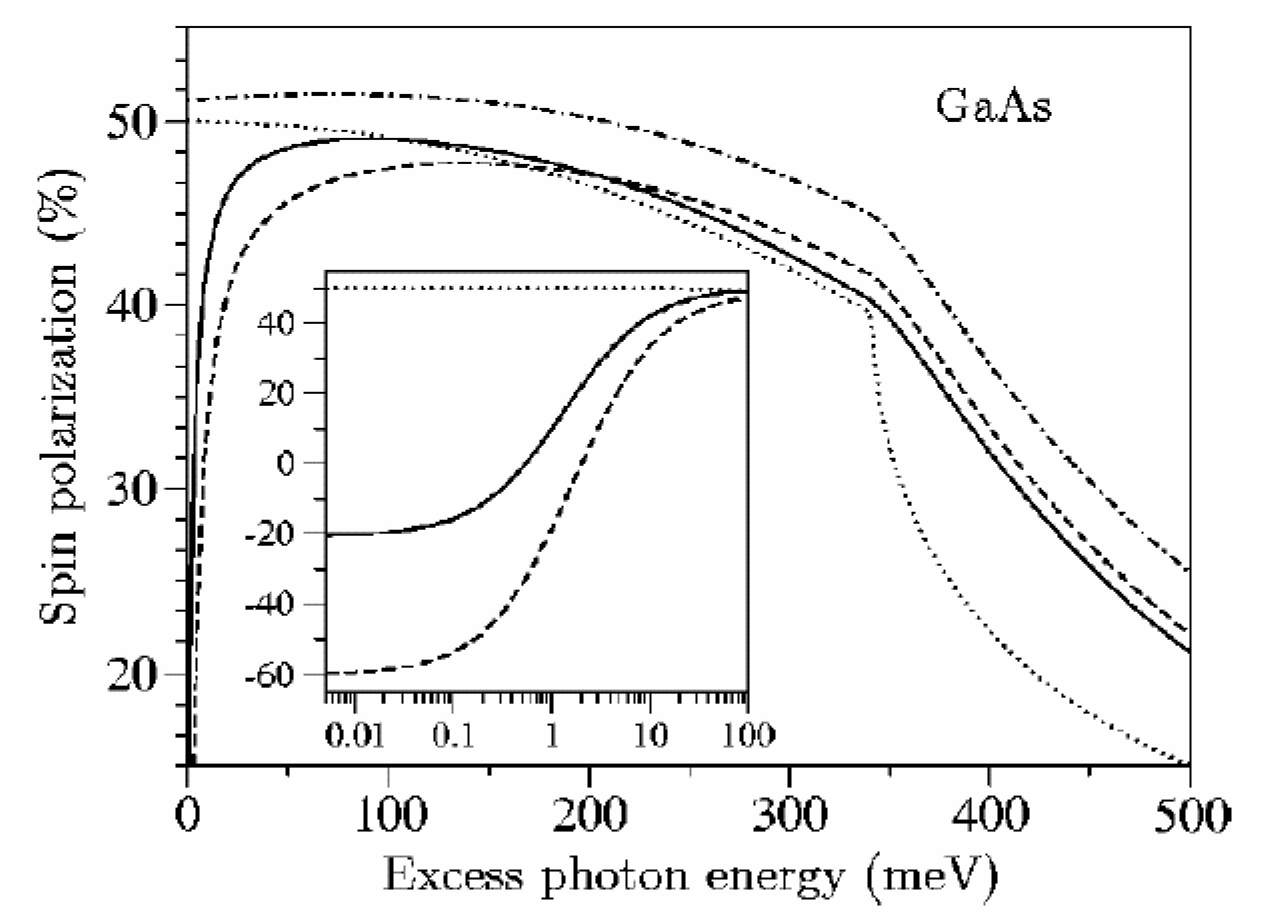


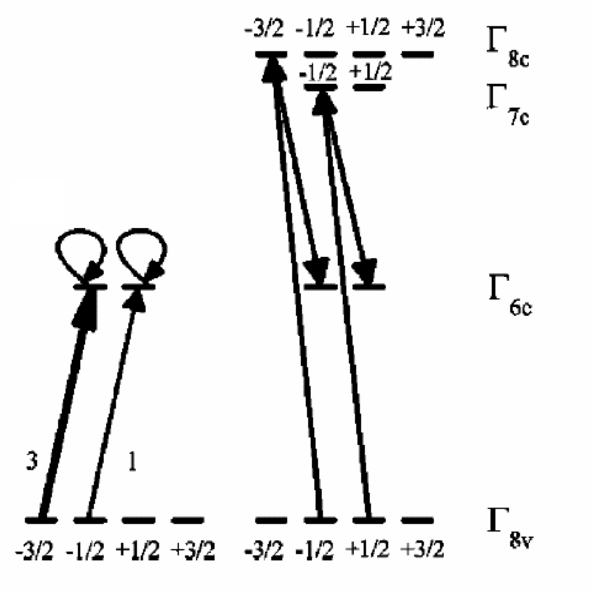


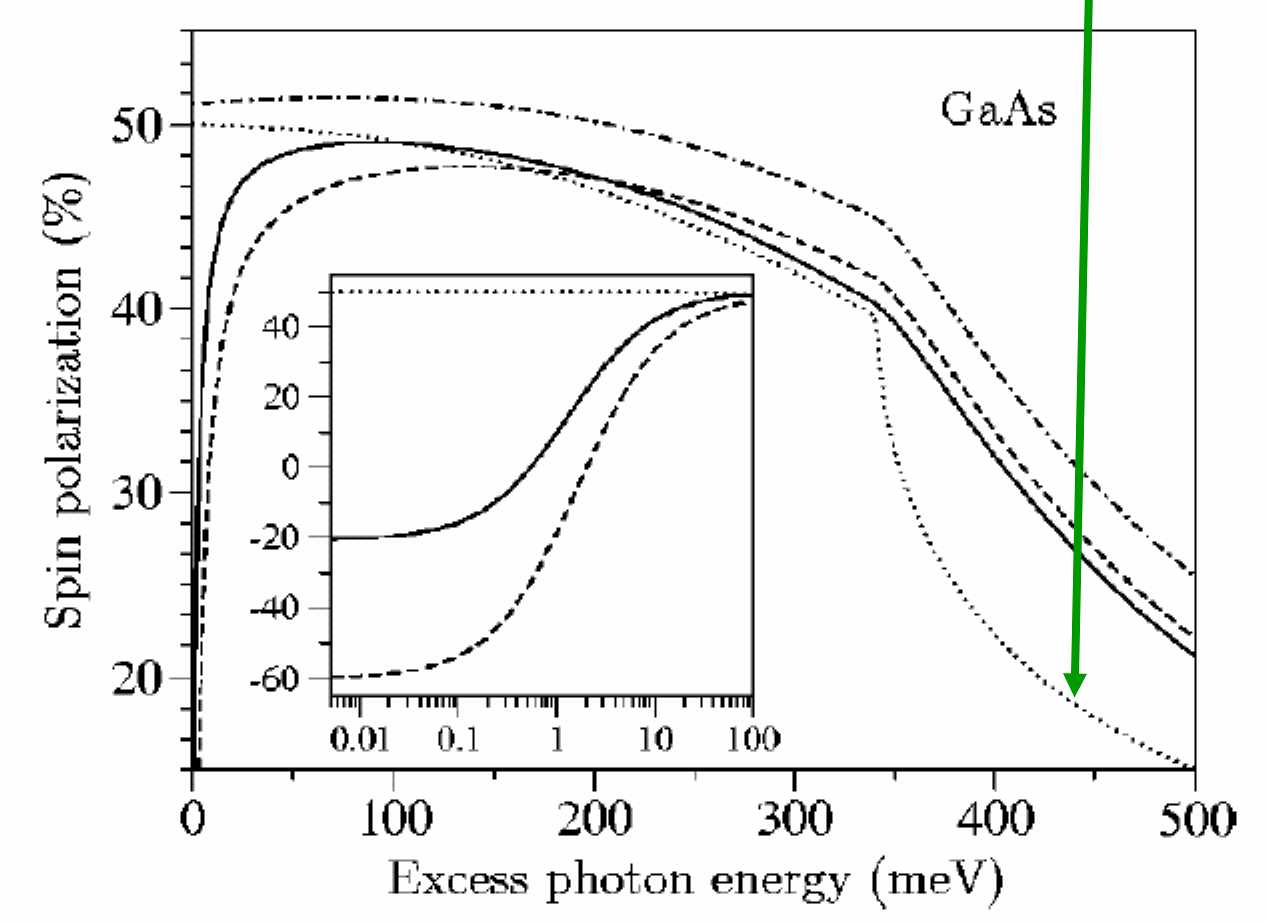
What happens in
two-photon absorption?


-3/2
-1/2
+1/2
+3/2
Γ8c
-1/2
+1/2
Γ7c
Γ6c
3
1
Γ8v
-3/2
-1/2
+1/2
+3/2
-3/2
-1/2
+1/2
+3/2

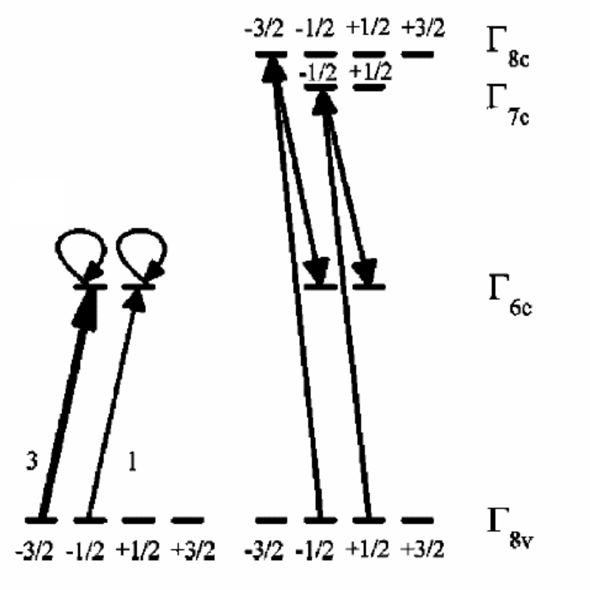

-3/2 -1/2 +1/2 +3/2
Γ8c
-1/2 +1/2
Γ7c
Γ6c
3
1
Γ8v
-3/2 -1/2 +1/2 +3/2 -3/2 -1/2 +1/2 +3/2

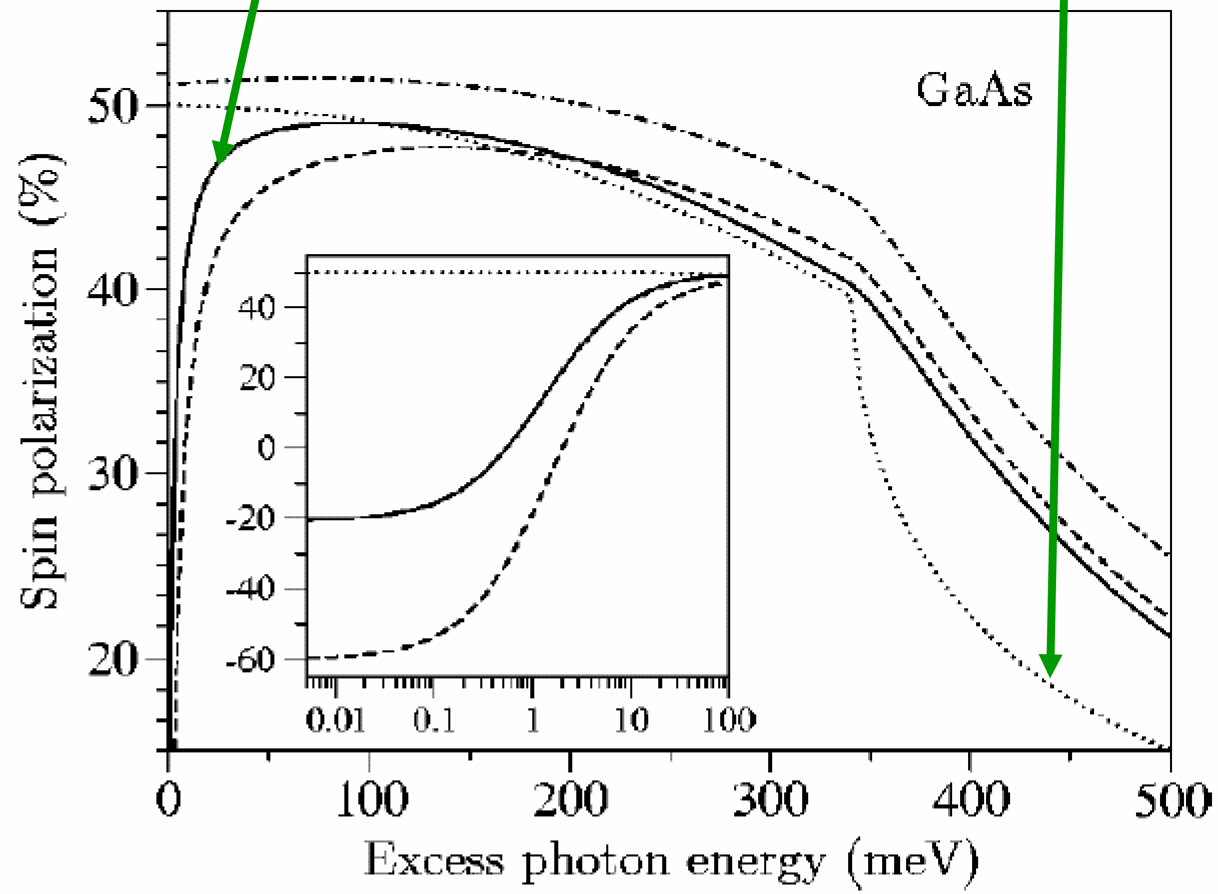

GaAs
Spin polarization (%)
50
40
30
20
0
100
200
300
400
500
Excess photon energy (meV)
40
20
0
-20
-40
-60
0.01
0.1
1
10
100





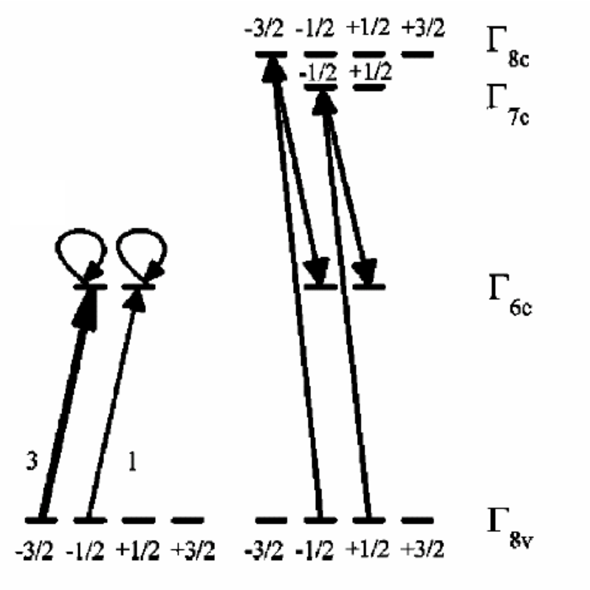
one-photon
absorption

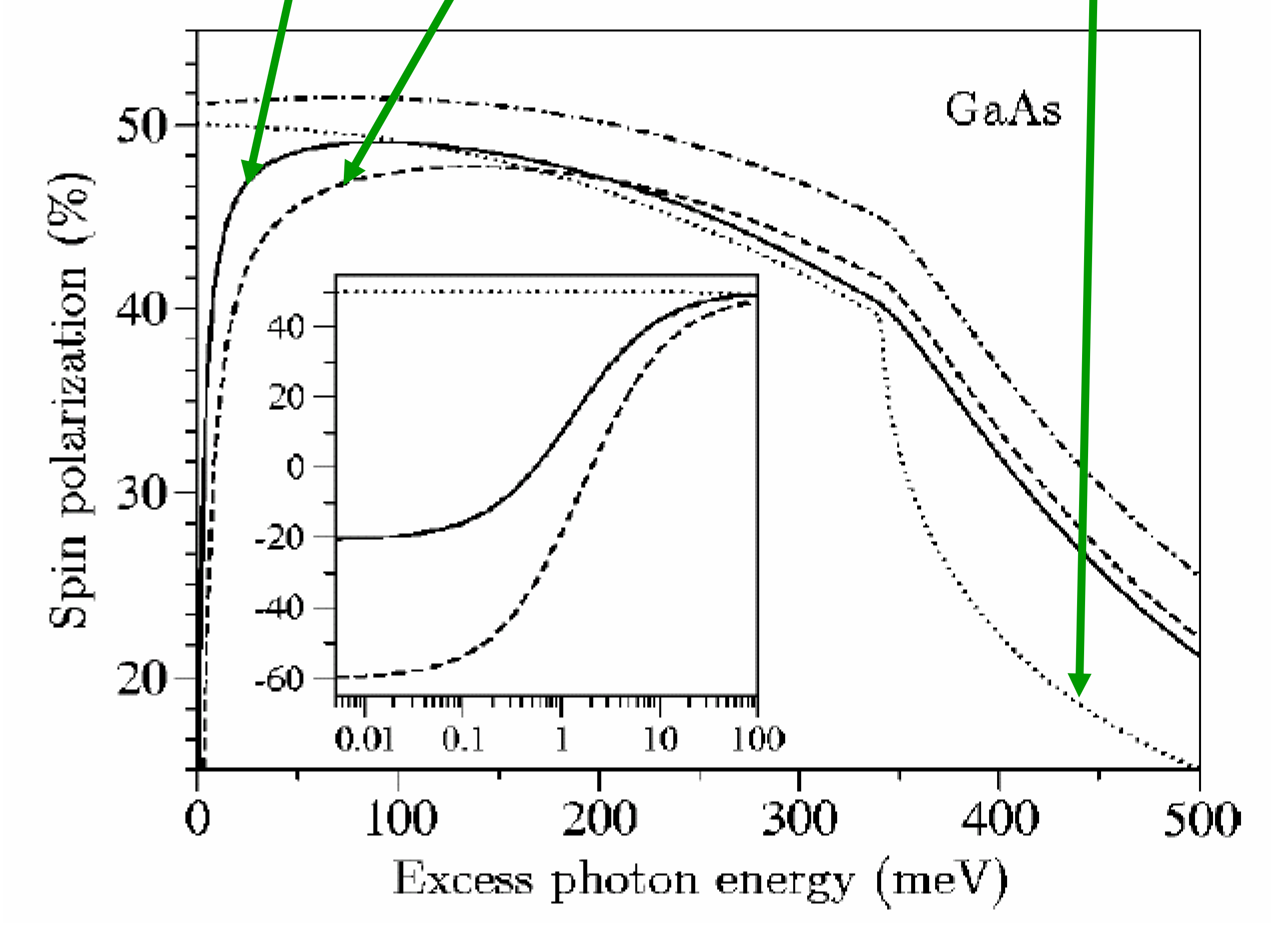




two-photon absorption
light along <001>

one-photon
absorption

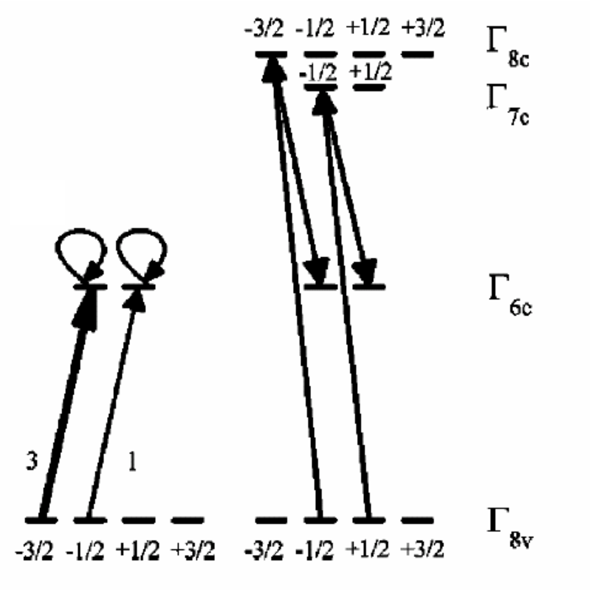


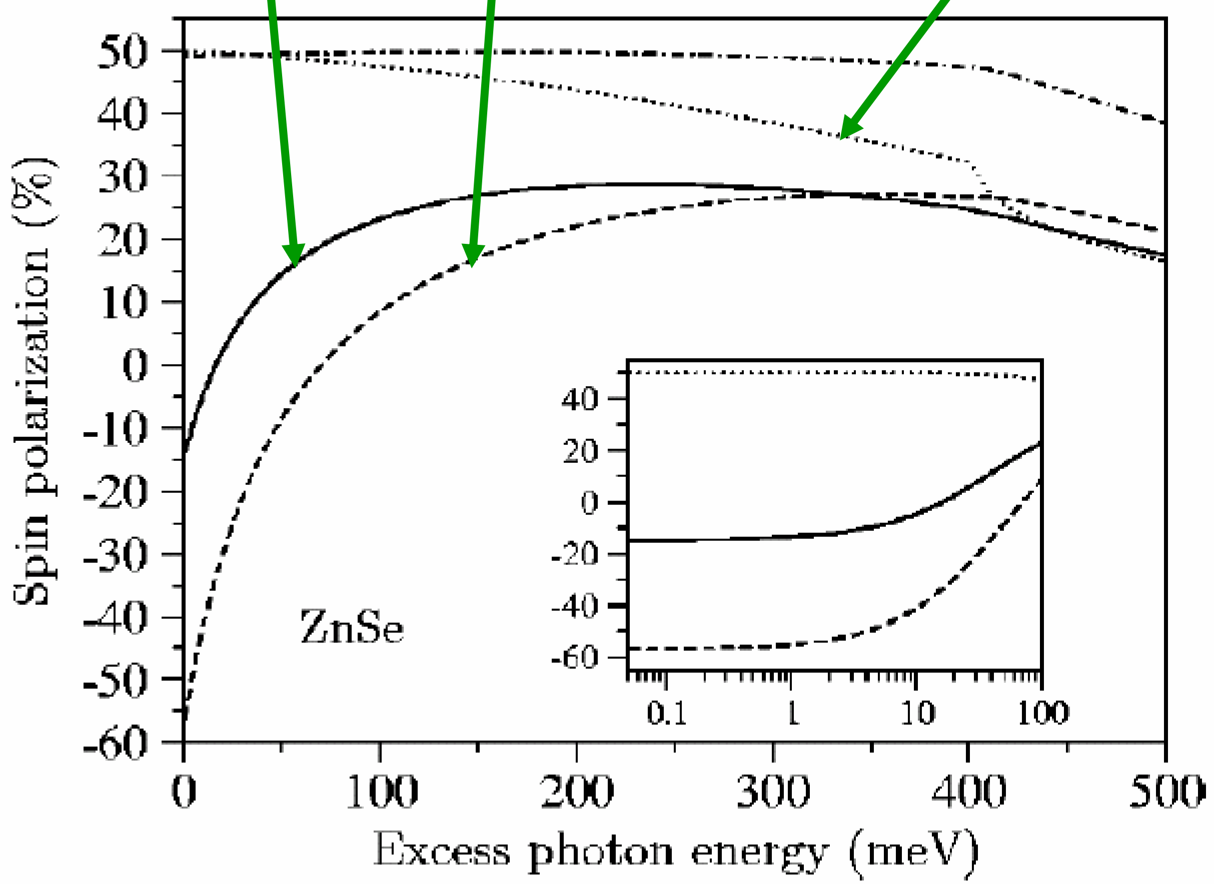


two-photon absorption
light along <001>

light along <111>

one-photon
absorption

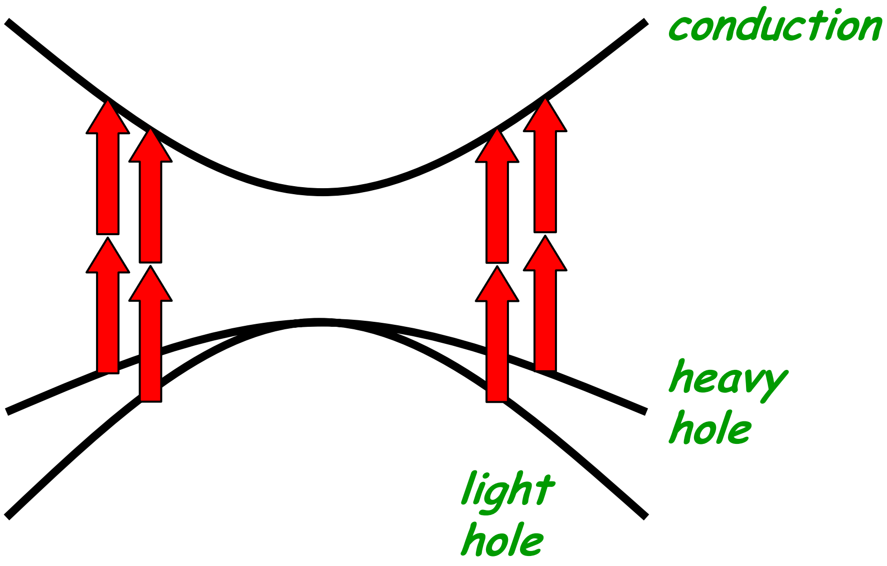


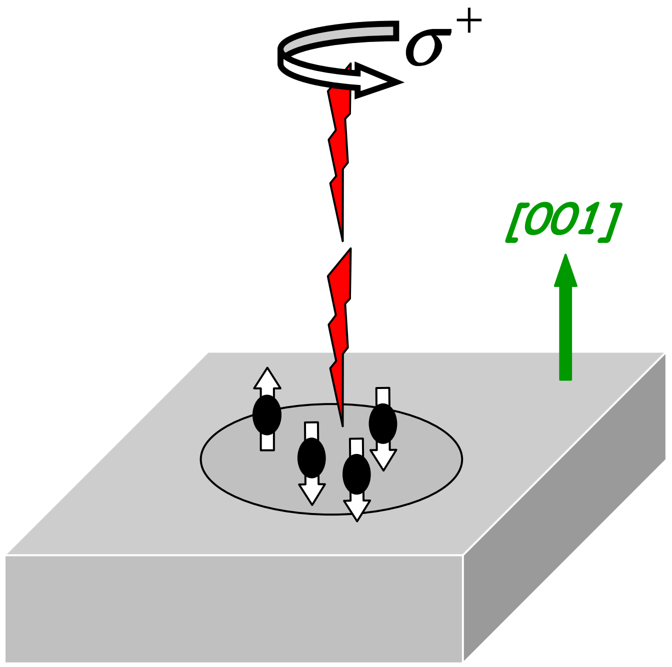


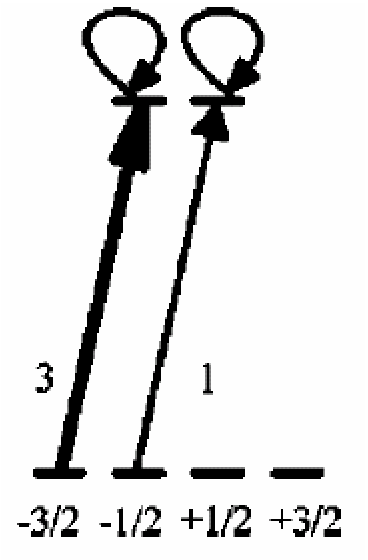
two-photon absorption
light along <001>

light along <111>

one-photon
absorption



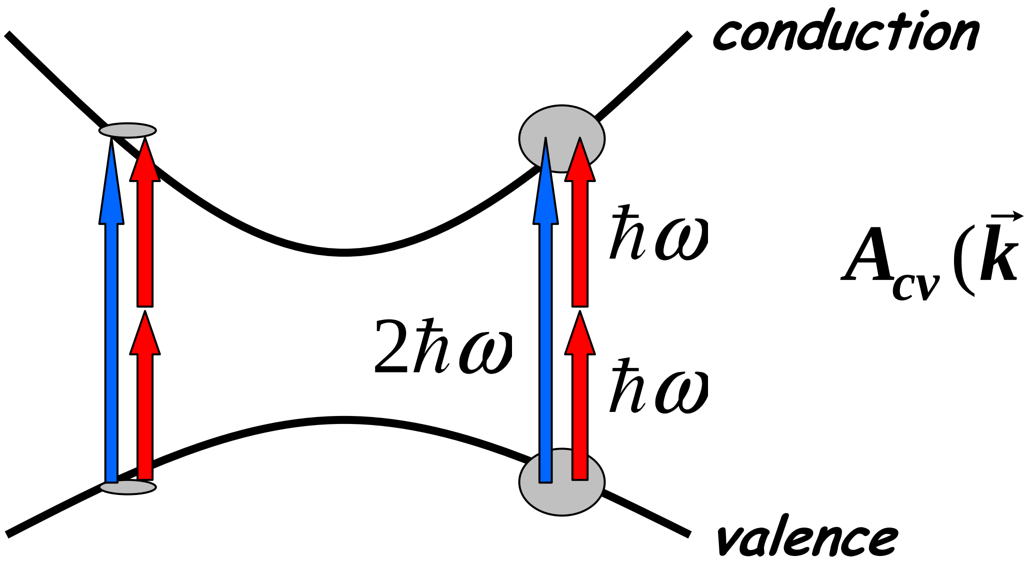




For GaAs, not too close to the gap, spin polarization ≈ 50%

R.D.R. Bhat et al.,
*Phys. Rev. **B71**, 035209 (2005)*
theory and experiment

coherent
current
control



$$A_{cv}(\vec{k}) = A_{cv}^{(1)}(\vec{k}) + A_{cv}^{(2)}(\vec{k})$$

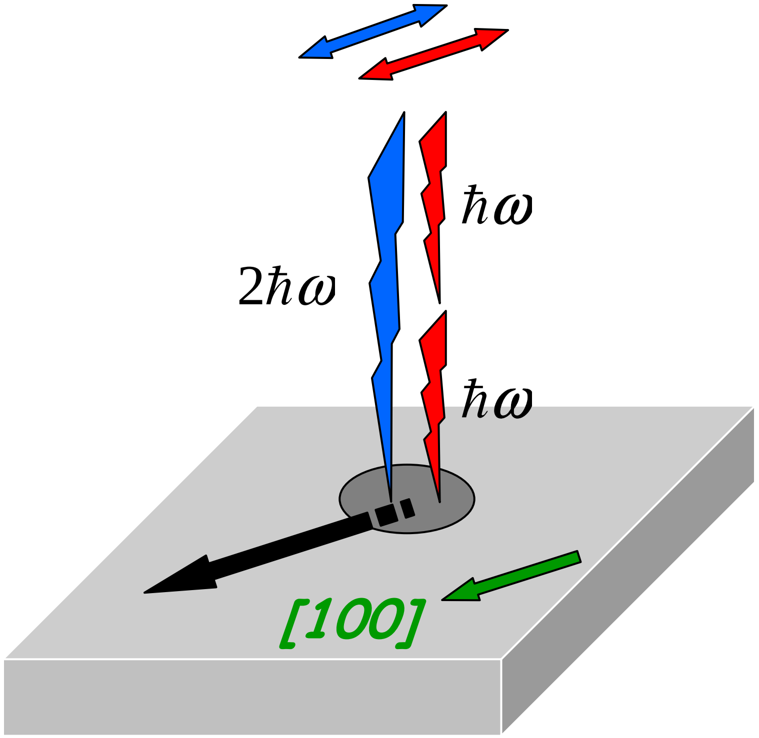
$$A_{cv}^{(1)}(\vec{k}) \quad \propto \quad \vec{p}_{cv}(\vec{k}) \cdot \vec{E}(2\omega)$$

$$A_{cv}^{(2)}(\vec{k}) \quad \propto \quad \sum_{n} \frac{\left[\vec{p}_{cn}(\vec{k}) \cdot \vec{E}(\omega)\right]\left[\vec{p}_{nv}(\vec{k}) \cdot \vec{E}(\omega)\right]}{\left[\omega_c(\vec{k}) + \omega_v(\vec{k}) - 2\omega_n(\vec{k})\right]}$$

simple experimental geometry:

$$\mathbf{E}(t) =$$

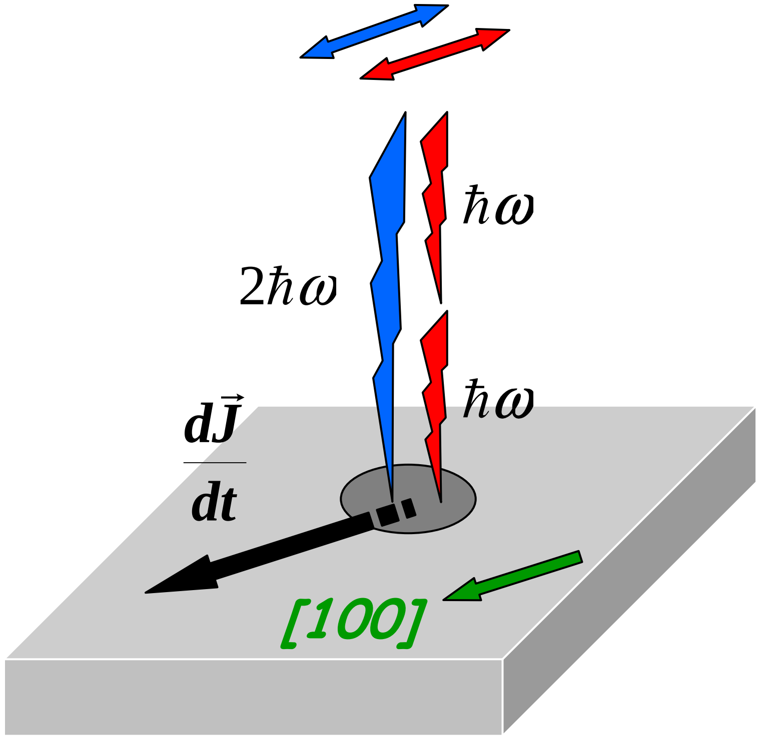
$$\hat{\mathbf{x}}\left(E_{2\omega}e^{i\phi_{2\omega}}e^{-2i\omega t}+E_{\omega}e^{i\phi_{\omega}}e^{-i\omega t}\right)$$



simple experimental geometry:

$$\mathbf{E}(t) =$$

$$\hat{\mathbf{x}}\left(E_{2\omega}e^{i\phi_{2\omega}}e^{-2i\omega t} + E_{\omega}e^{i\phi_{\omega}}e^{-i\omega t}\right)$$

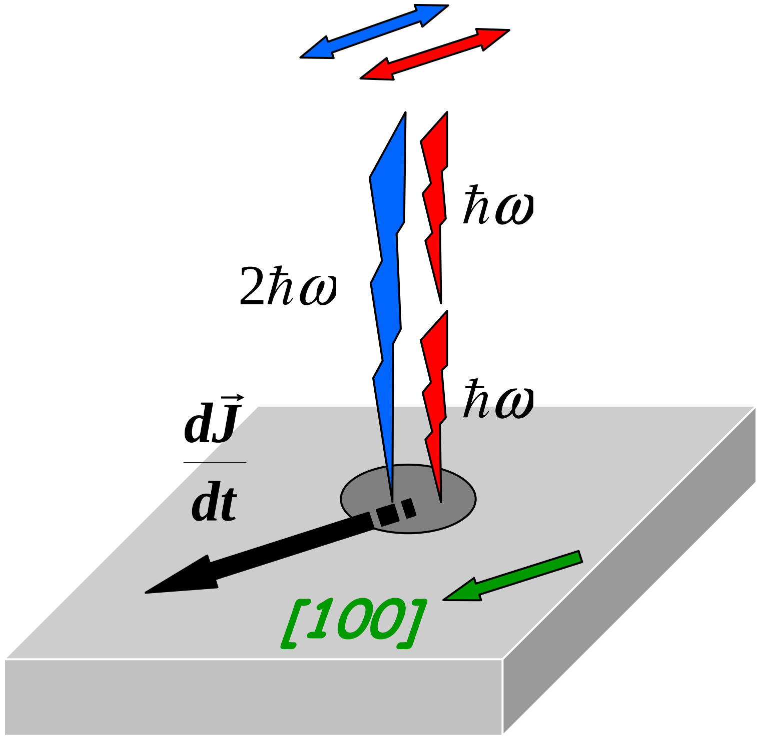


$$\frac{d\mathbf{J}}{dt} = 2E_{\omega}^{2}E_{2\omega}\left|\eta_{(I)}^{xxxx}\right|\hat{\mathbf{x}}\sin(2\phi_{\omega} - \phi_{2\omega} - \delta^{xxxx})$$

simple experimental geometry:

$$\mathbf{E}(t) =$$

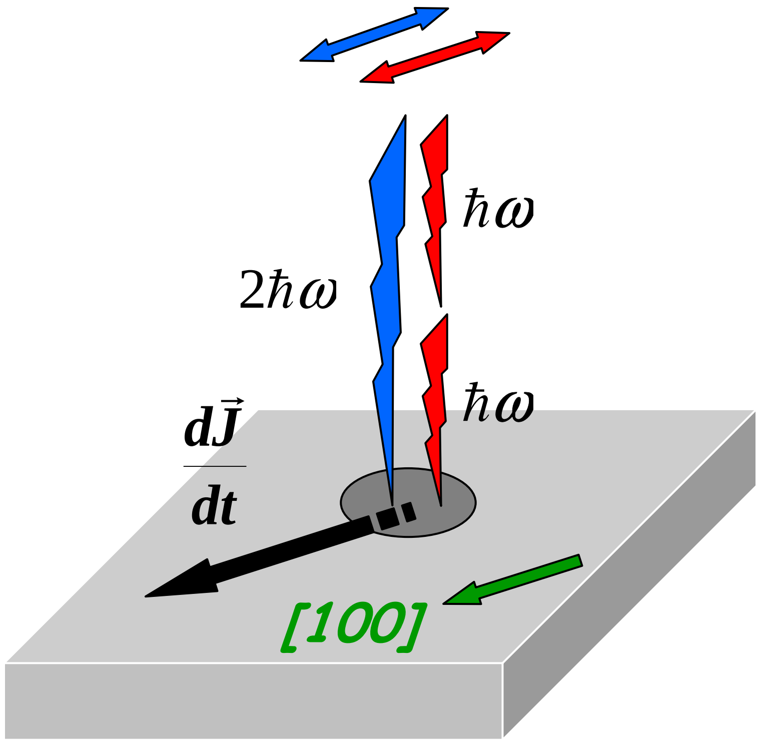
$$\hat{\mathbf{x}}\left(E_{2\omega}e^{i\phi_{2\omega}}e^{-2i\omega t} + E_{\omega}e^{i\phi_{\omega}}e^{-i\omega t}\right)$$



$$\frac{d\mathbf{J}}{dt} = 2E_{\omega}^{2}E_{2\omega}\left|\eta_{(I)}^{xxxx}\right|\hat{\mathbf{x}}\sin(\underbrace{2\phi_{\omega} - \phi_{2\omega}}_{\text{control parameter}} - \delta^{xxxx})$$

simple experimental geometry:

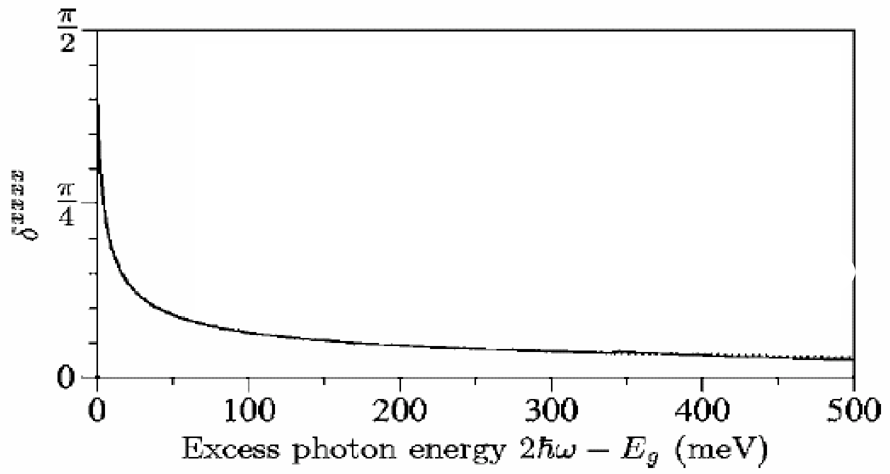
$$\mathbf{E}(t) = \hat{\mathbf{x}}\left(E_{2\omega}e^{i\phi_{2\omega}}e^{-2i\omega t} + E_{\omega}e^{i\phi_{\omega}}e^{-i\omega t}\right)$$

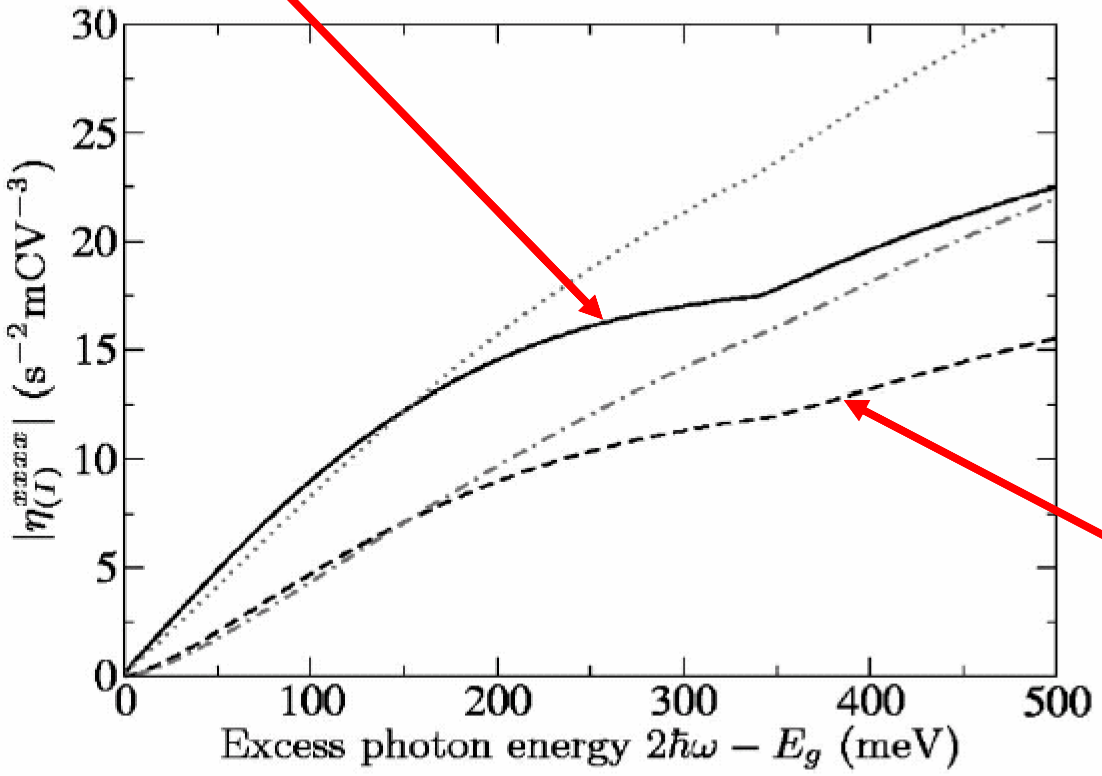


phase shift due to
e-h interaction

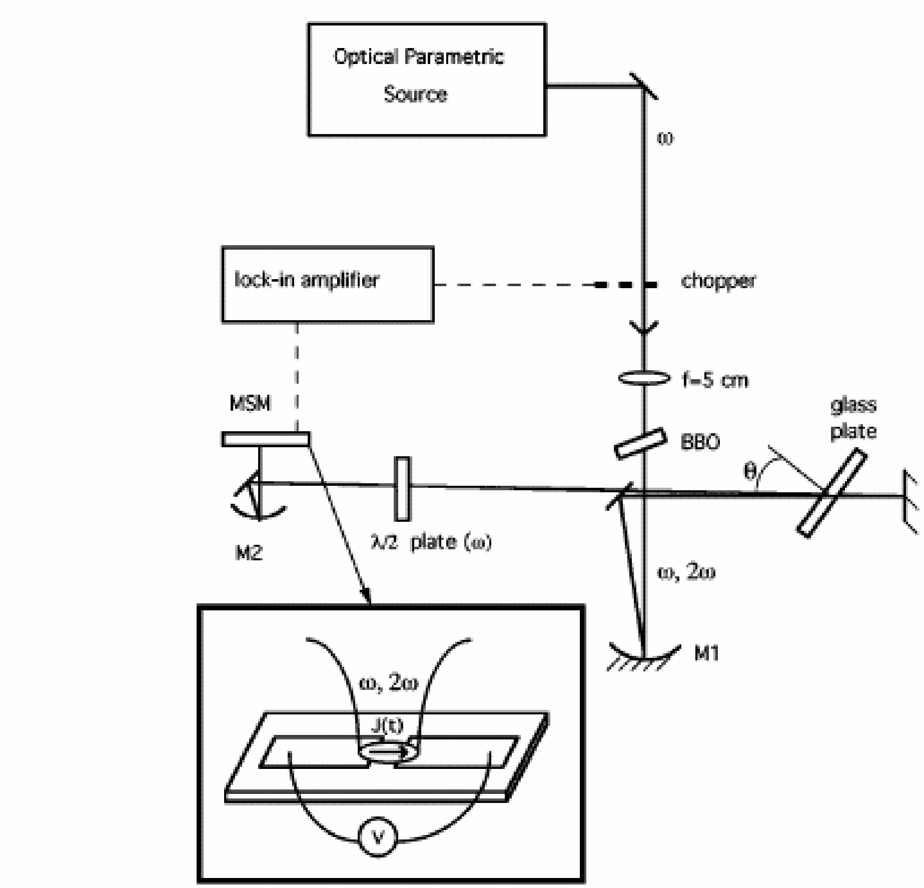
$$\frac{d\mathbf{J}}{dt} = 2E_{\omega}^{2}E_{2\omega}\left|\eta_{(I)}^{xxxx}\right|\hat{\mathbf{x}}\sin(\underbrace{2\phi_{\omega} - \phi_{2\omega}}_{\text{control parameter}} - \delta^{xxxx})$$

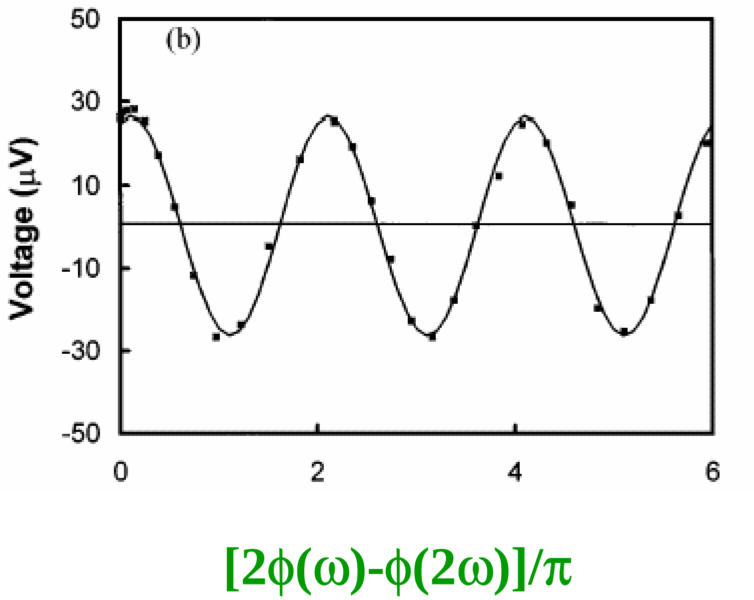
including e-h interaction



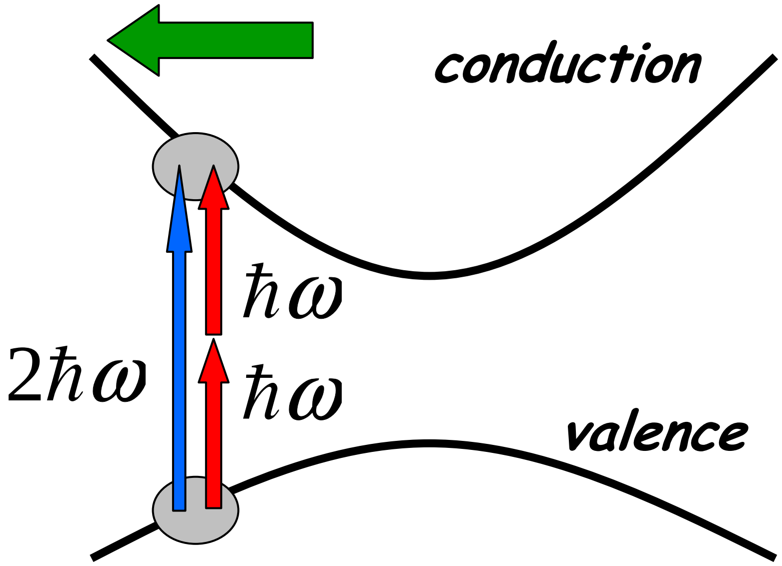


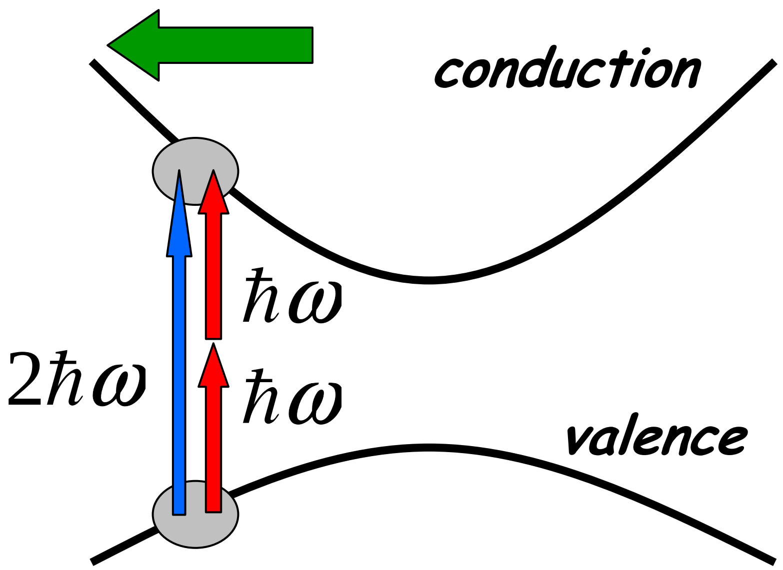
neglecting e-h interaction

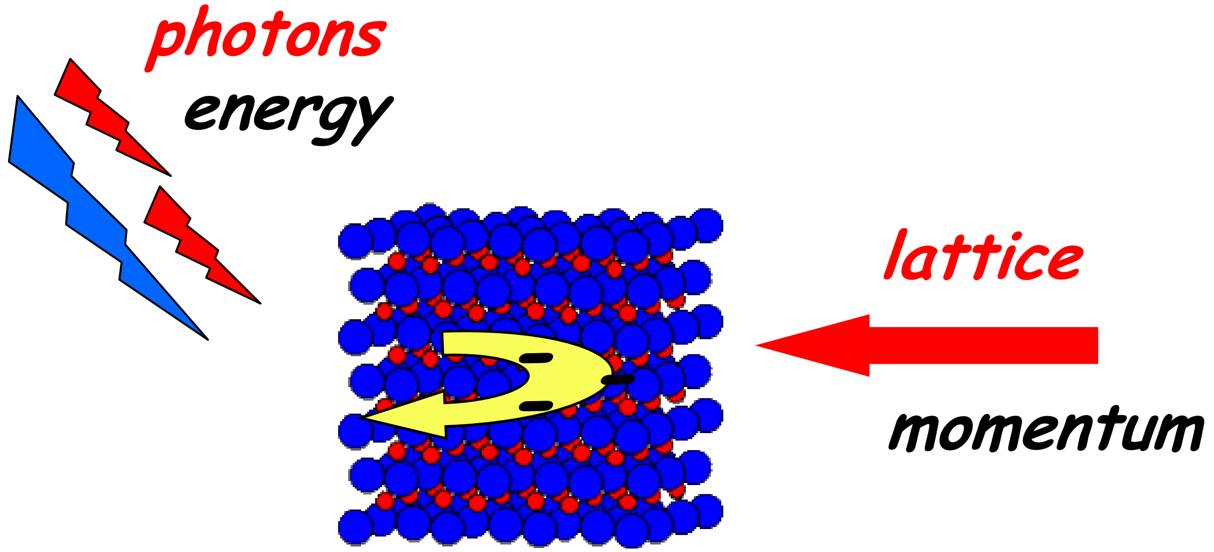


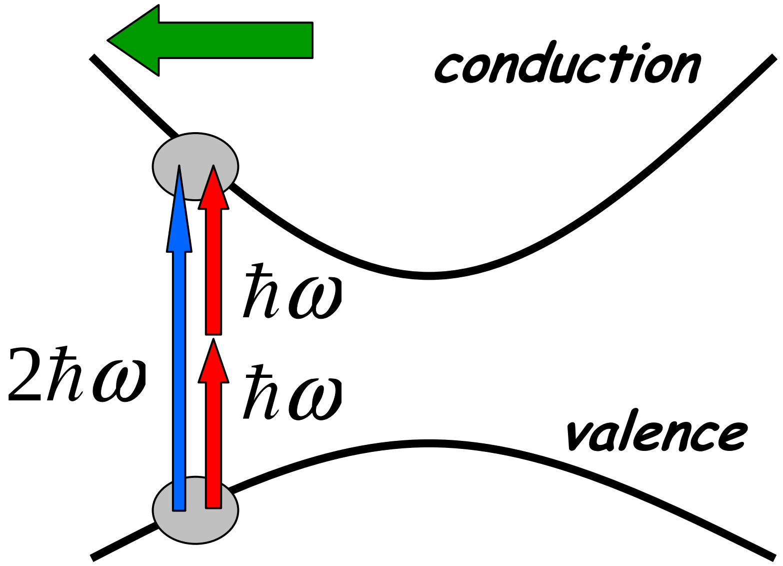


A. Hache' et al.,
Phys. Rev. Lett. ***78****, 306 (1997)*


conduction
$\hbar\omega$
$2\hbar\omega$
$\hbar\omega$
valence


conduction
$\hbar\omega$
$2\hbar\omega$
$\hbar\omega$
valence


photons
energy
lattice
momentum



gasoline

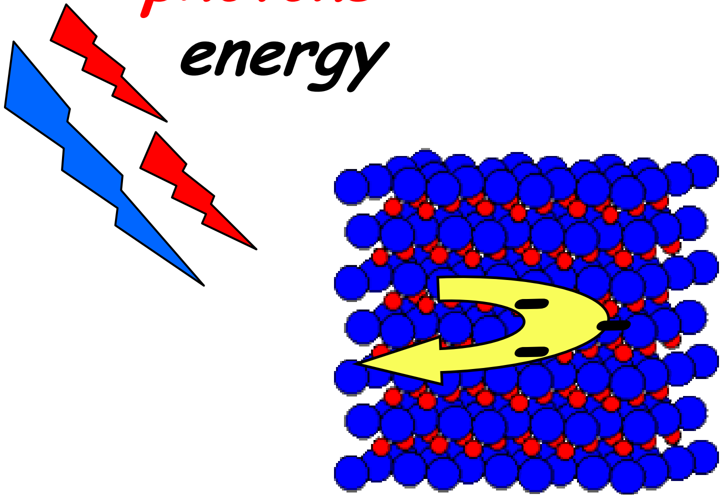
energy

road

momentum

photons

energy

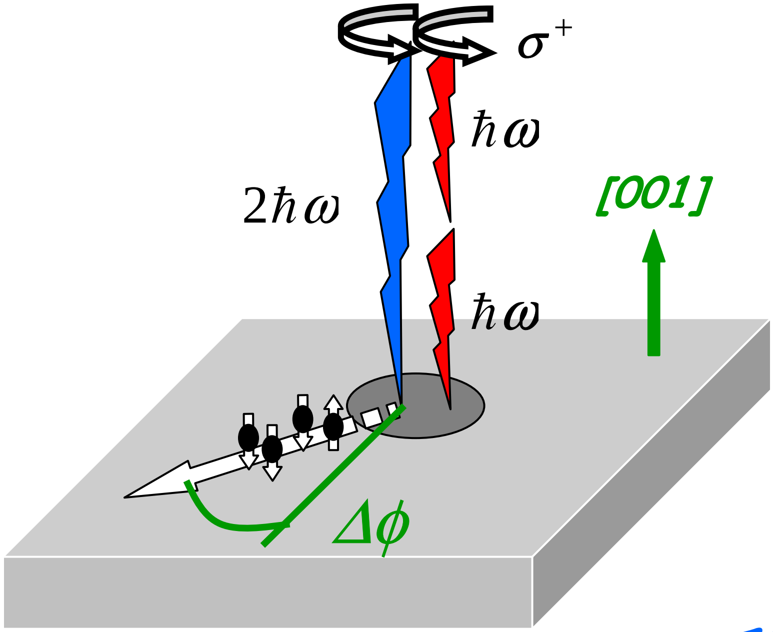


lattice

momentum

Two-colour processes

Same circular polarizations

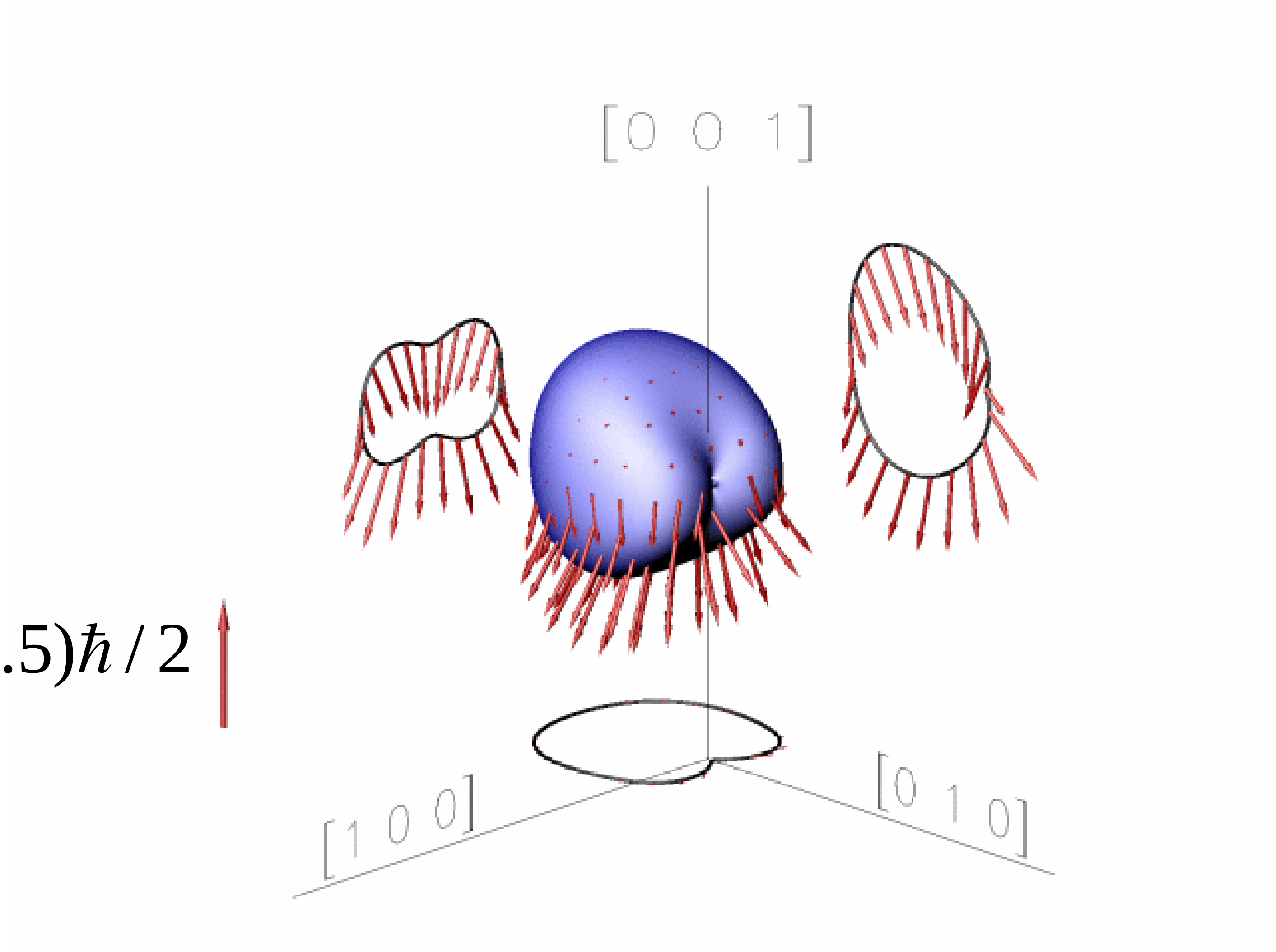


$\frac{d\vec{J}}{dt}$ and $\frac{dK^{ab}}{dt}$

$$K^{ab} \equiv \langle v^a S^b \rangle$$

spin polarized current

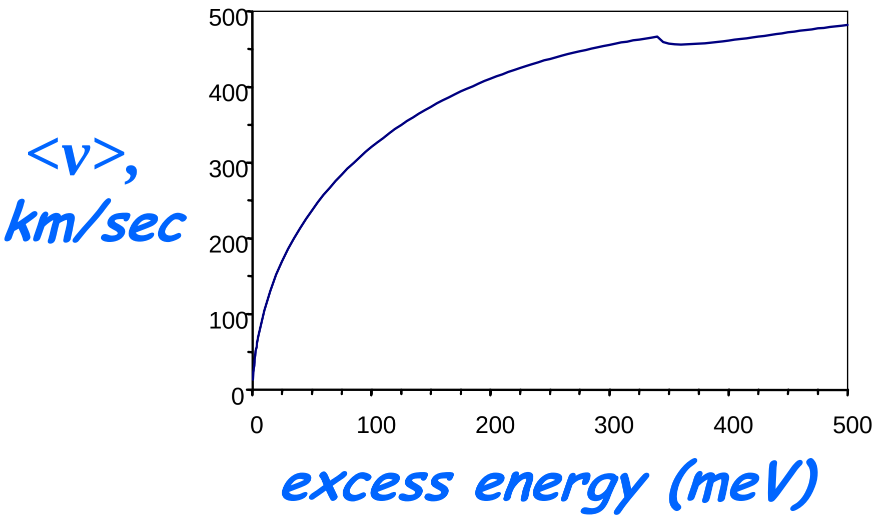
direction $\Delta\phi$ of current from crystal axis
depends on relative phase parameter
$\phi(2\omega)-2\phi(\omega)$ ***of optical fields***



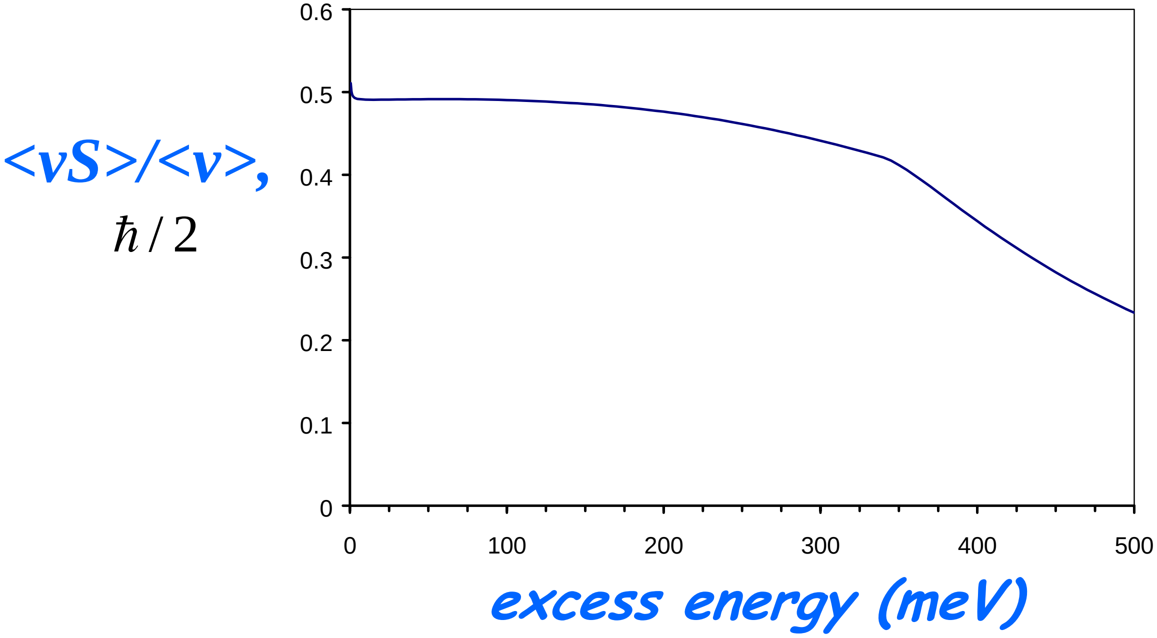
$(0.5)\hbar/2$

100 meV excess energy

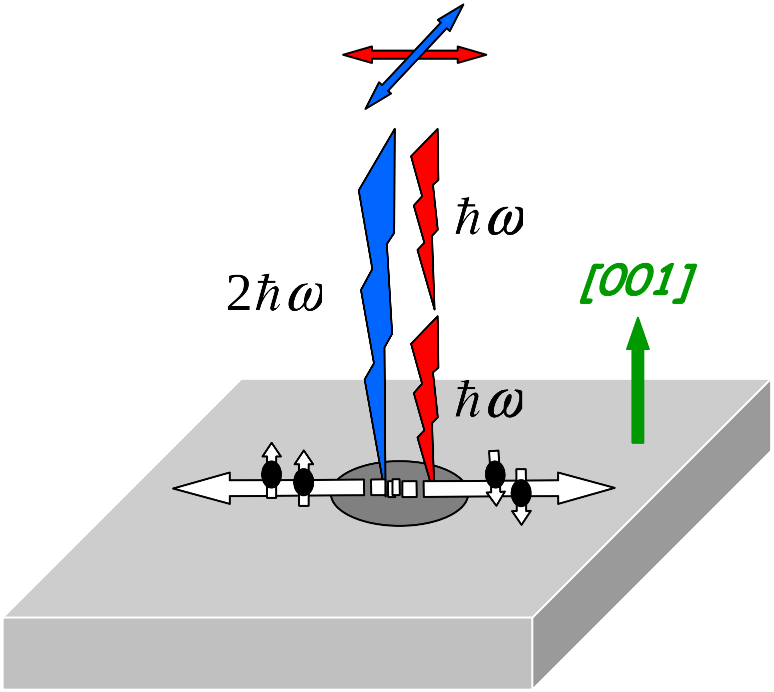
injection velocity



spin polarization



Crossed linear polarizations



no spin injection

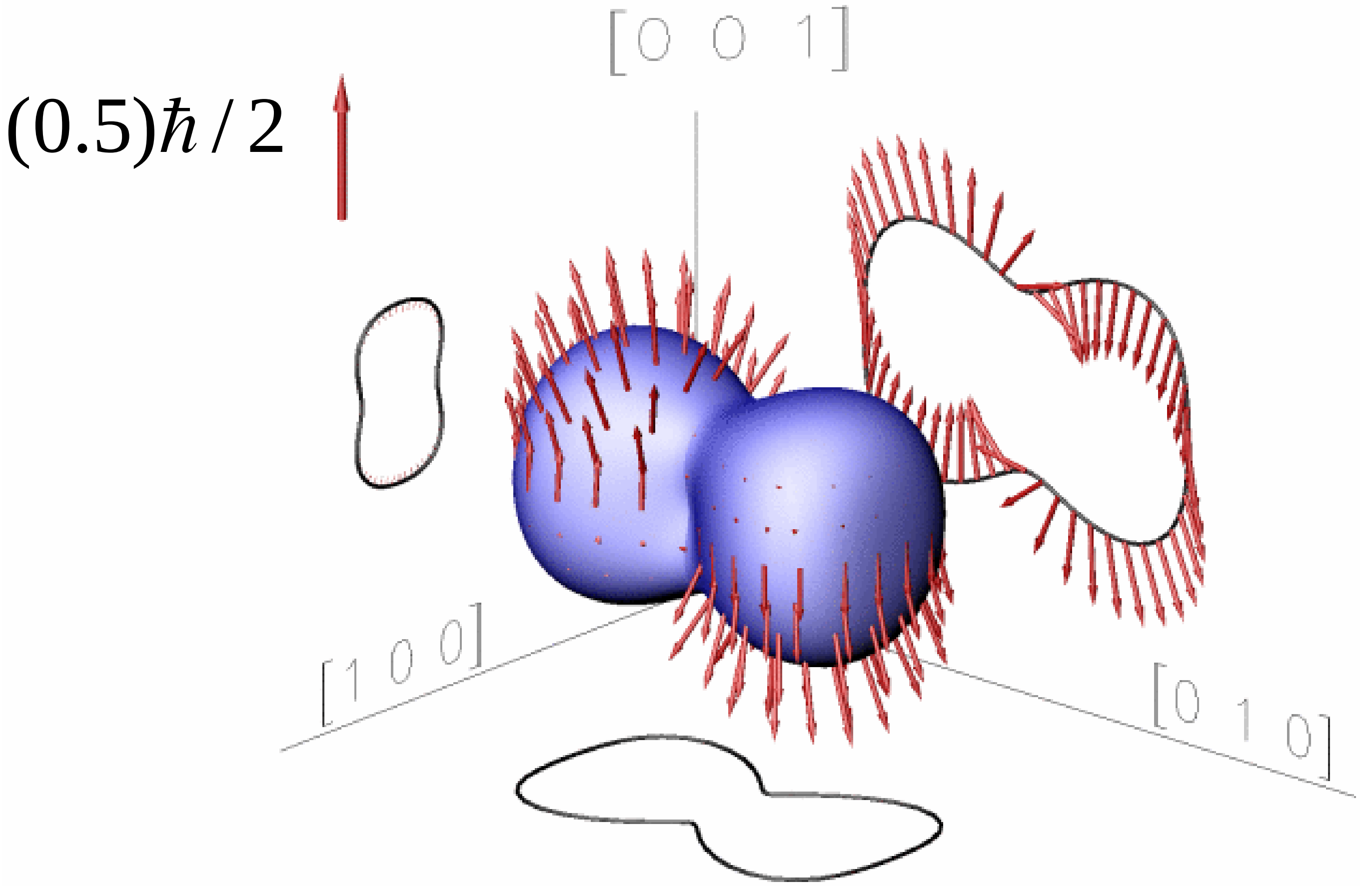
pure spin current

only $\dfrac{dK^{ab}}{dt}$

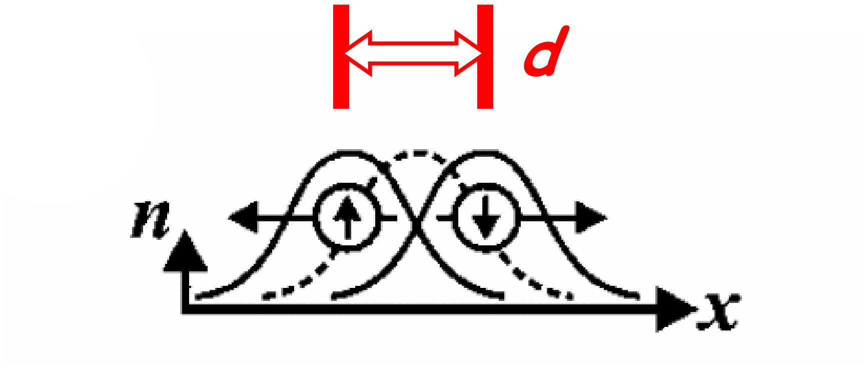
$$K^{ab} \equiv \left\langle v^a S^b \right\rangle$$

magnitude of pure spin current varies as

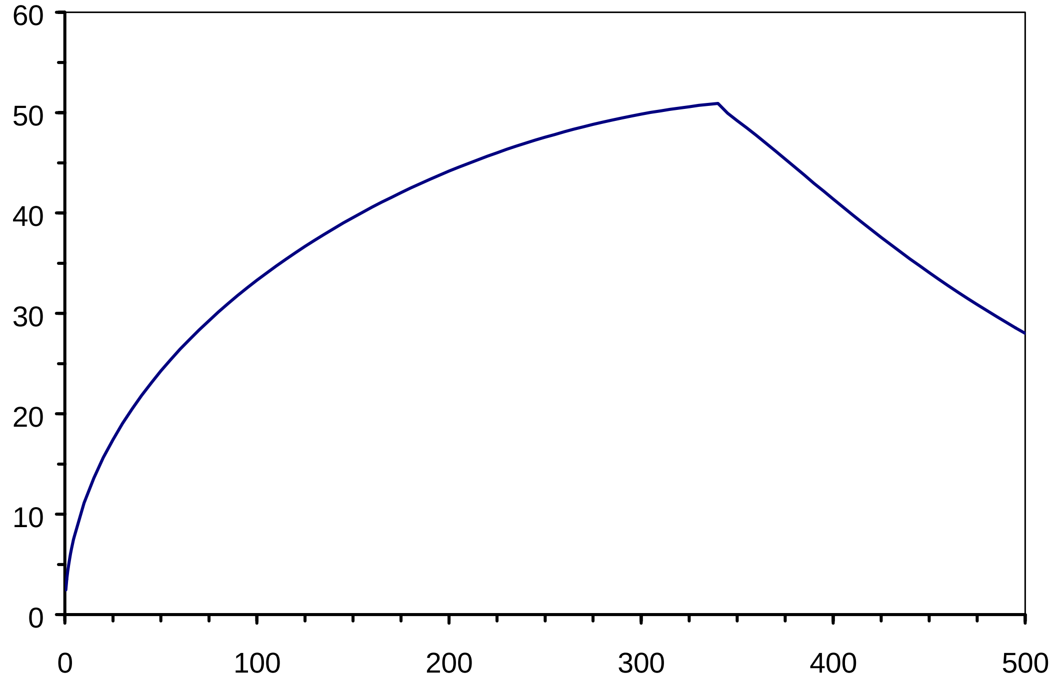
$$\cos\left(\phi(2\omega)-2\phi(\omega)\right)$$



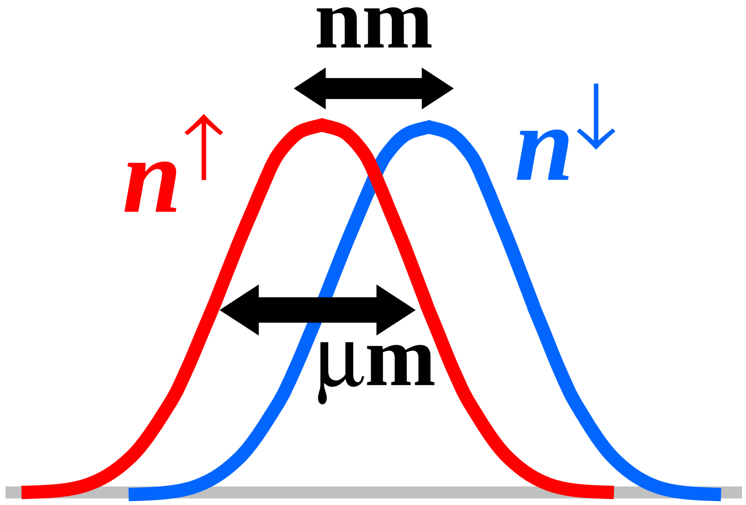
100 meV excess energy

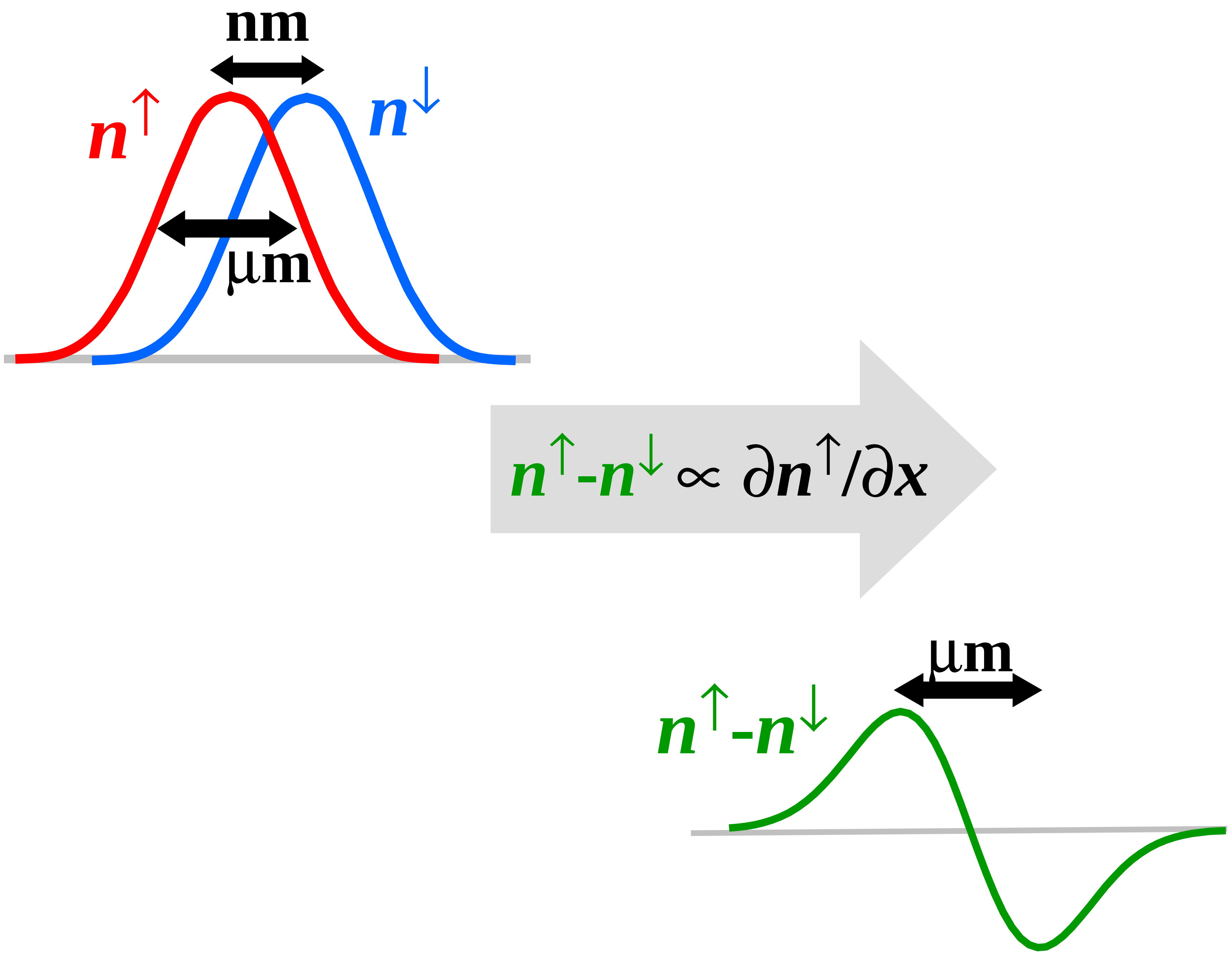


spin separation d, nm (for τ =100 fs)

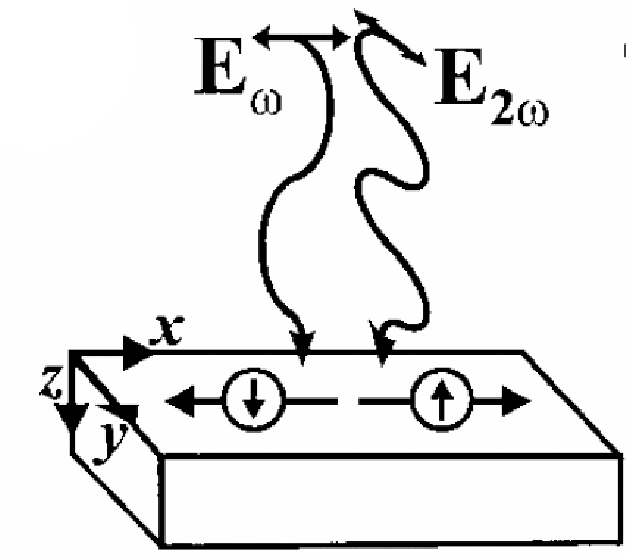


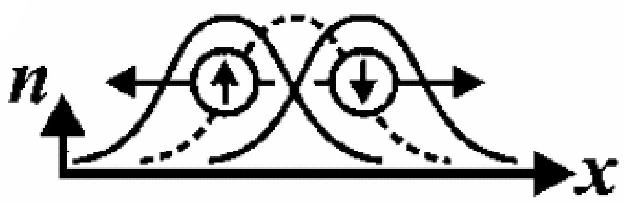
excess energy (meV)


nm
$n^{\uparrow}$
$n^{\downarrow}$
μm

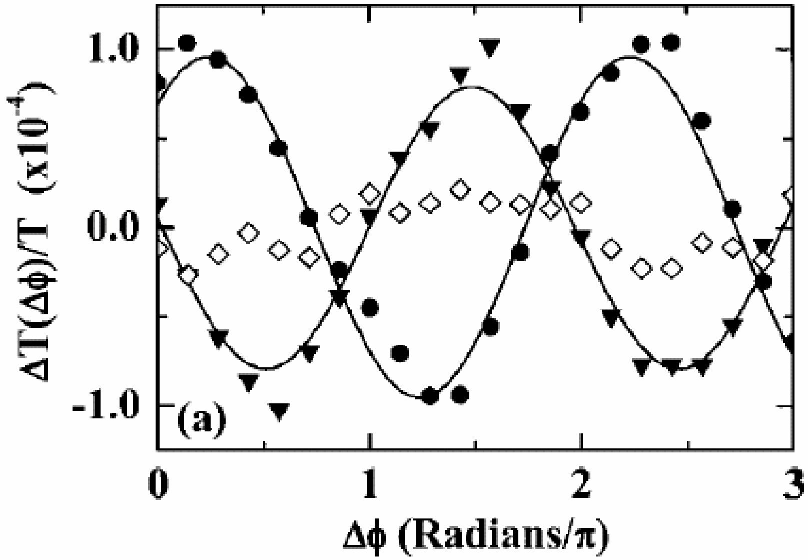


$$n^{\uparrow} - n^{\downarrow} \propto \partial n^{\uparrow}/\partial x$$

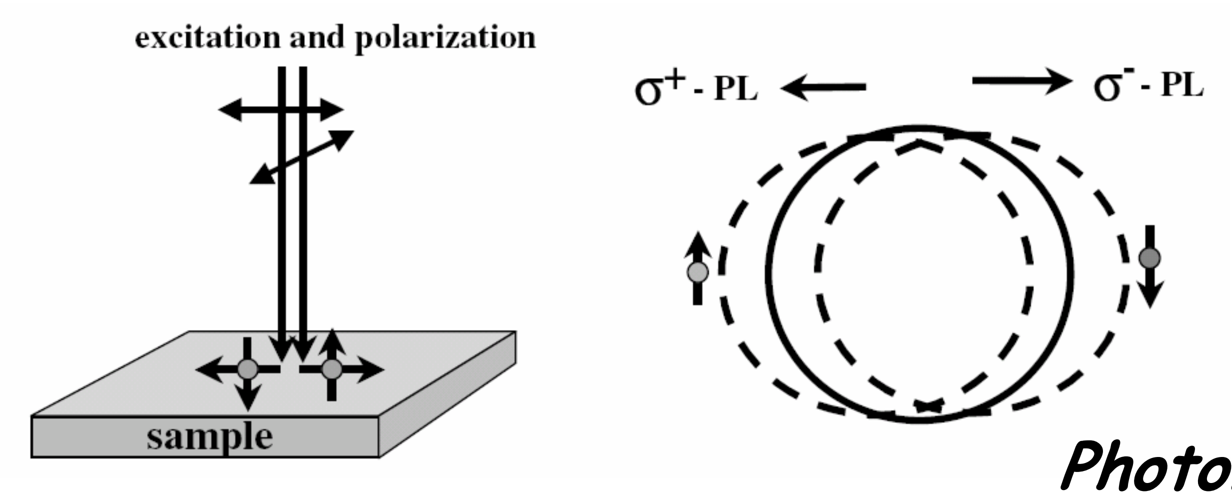




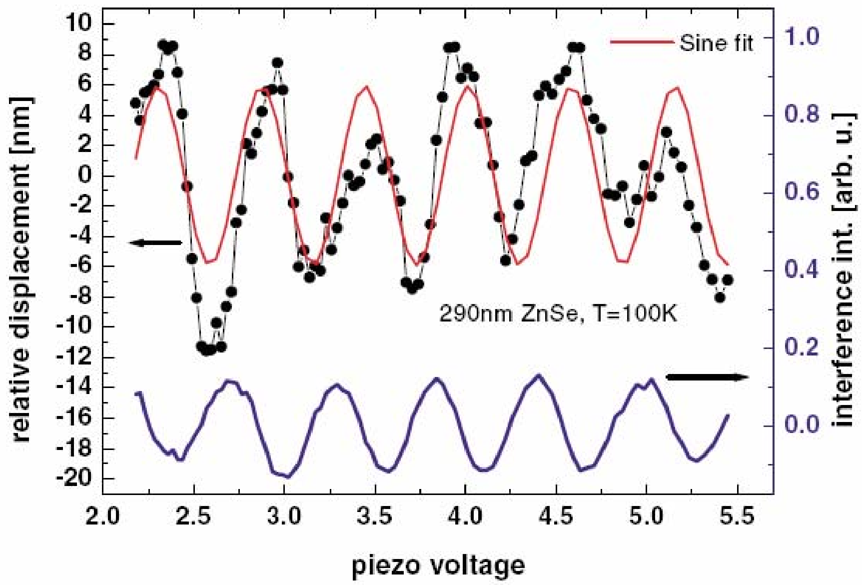
Pump-probe detection:



M.J. Stevens et al.
Phys. Rev. Lett. ***90****, 136603*
(2003)

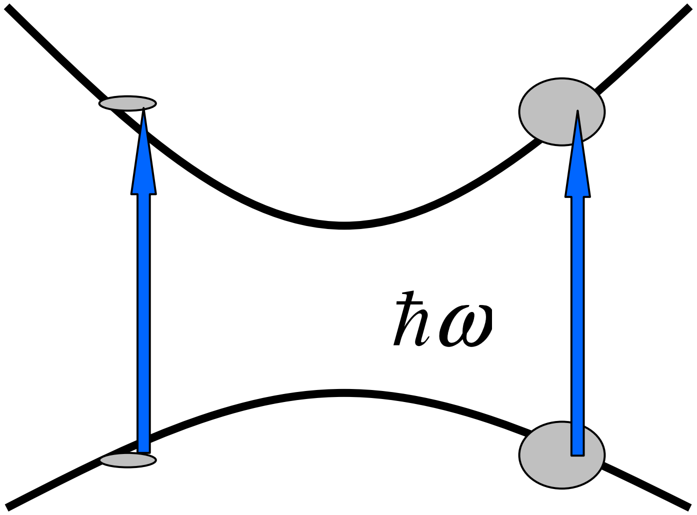


Photoluminescence detection:

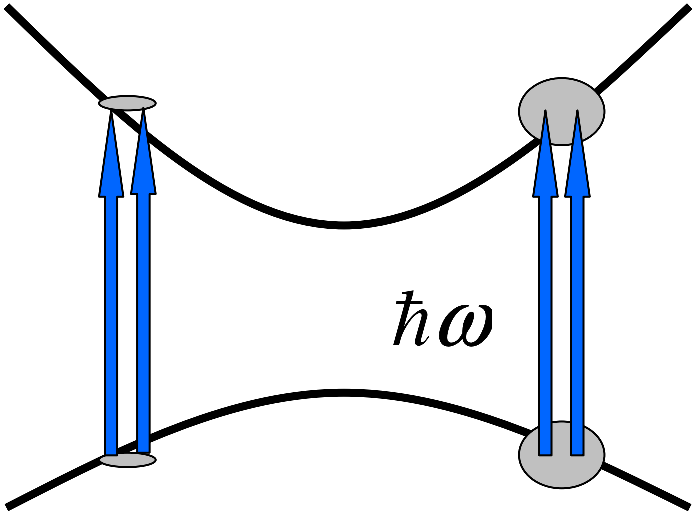


Jens Hübner et al.,
Phys. Rev. Lett. ***90****, 216601*
(2003)

One-colour processes

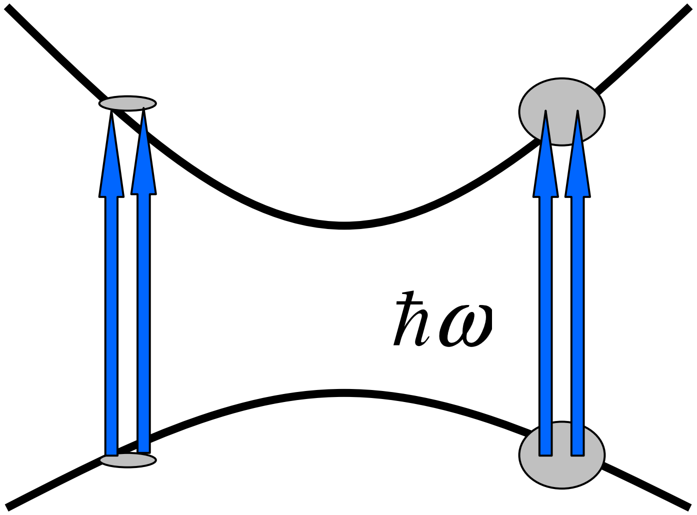


$$\boldsymbol{A}_{cv}^{(1)}(\vec{\boldsymbol{k}}) \quad \propto \quad \vec{\boldsymbol{p}}_{cv}(\vec{\boldsymbol{k}})\cdot\vec{\boldsymbol{E}}(\omega)$$



$$A_{cv}^{(1)}(\vec{k}) \propto \vec{p}_{cv}(\vec{k})\cdot\vec{E}(\omega)$$

$$A_{cv}^{(1)}(\vec{k}) \propto p_{cv}^{x}(\vec{k})E^{x}(\omega)+p_{cv}^{z}(\vec{k})E^{z}(\omega)$$

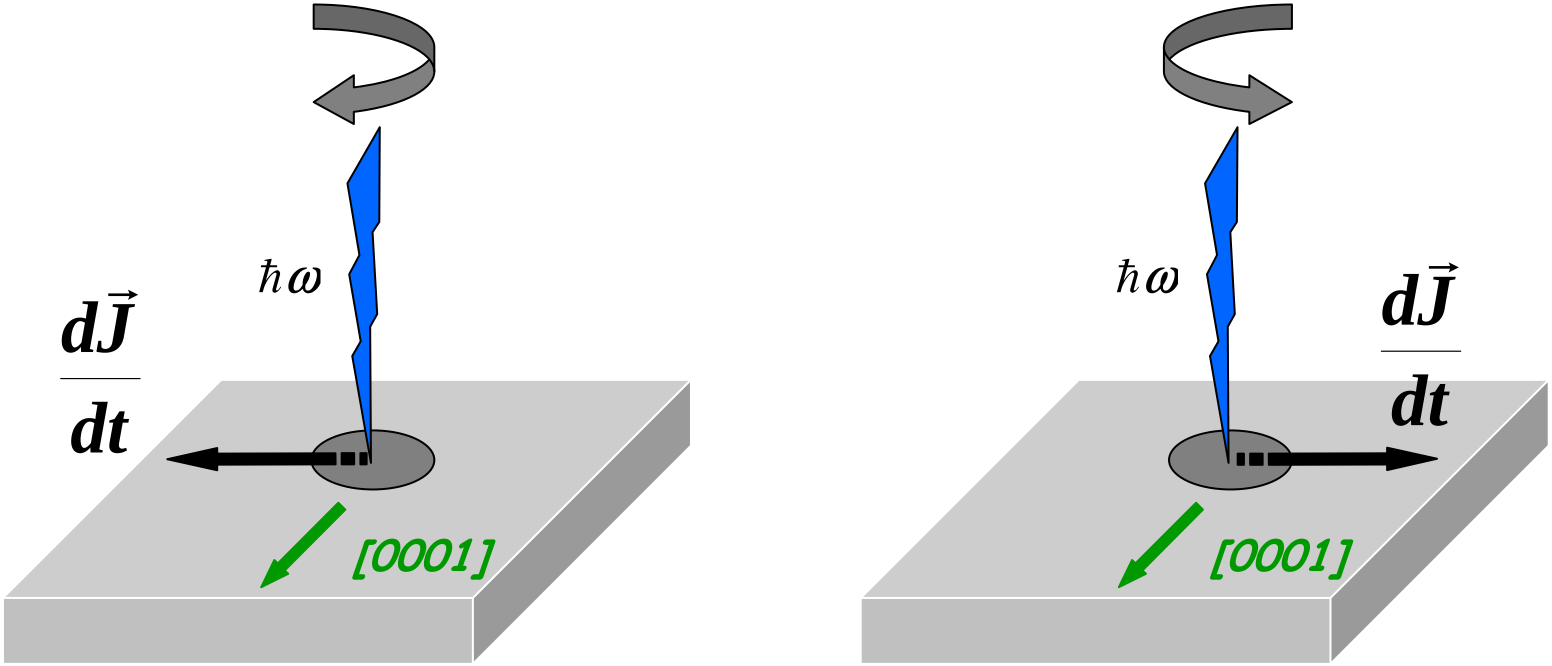


$$A_{cv}^{(1)}(\vec{k}) \quad \propto \quad \vec{p}_{cv}(\vec{k})\cdot\vec{E}(\omega)$$

$$A_{cv}^{(1)}(\vec{k}) \quad \propto \quad p_{cv}^{x}(\vec{k})E^{x}(\omega)+p_{cv}^{z}(\vec{k})E^{z}(\omega)$$

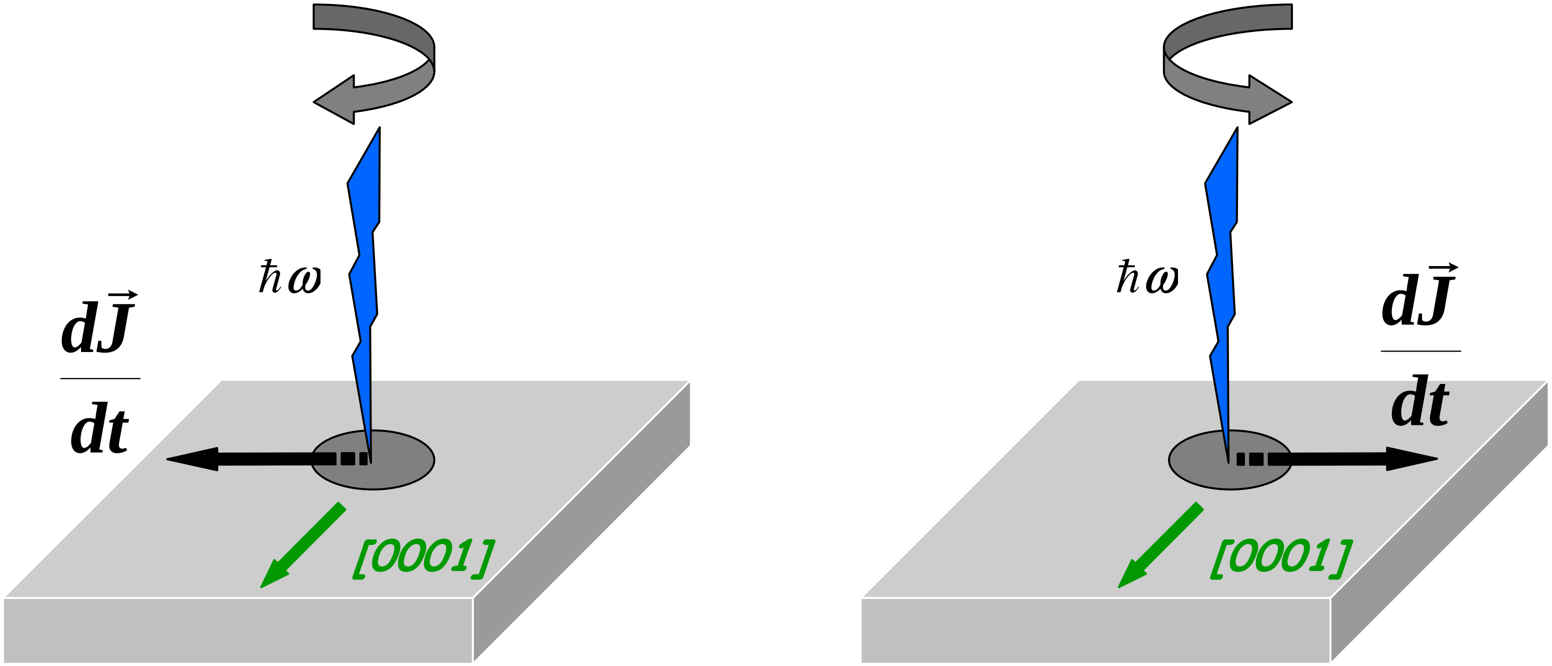
$$\frac{dJ^{a}}{dt}=\eta^{acd}(\omega)E^{c}(-\omega)E^{d}(\omega)+c.c.$$

injection proportional to intensity



direction of current from crystal axis depends on helicity of beam

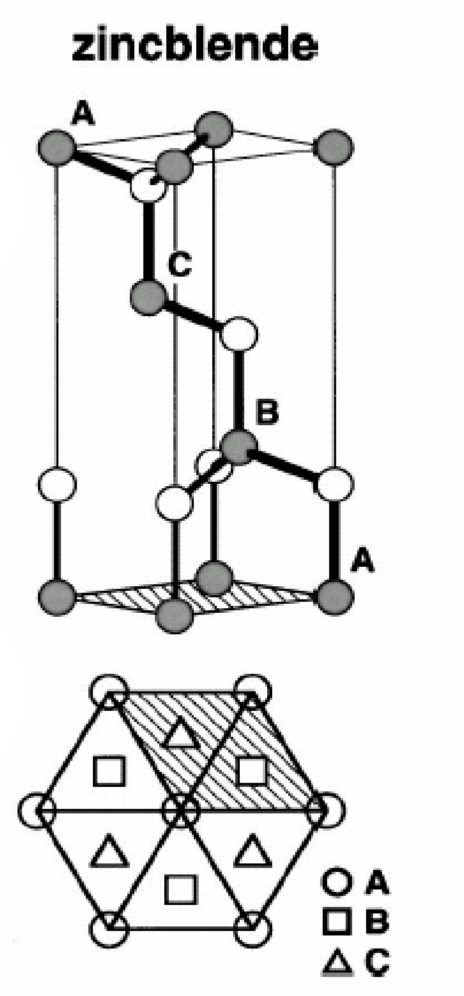
Circular photogalvanic effect



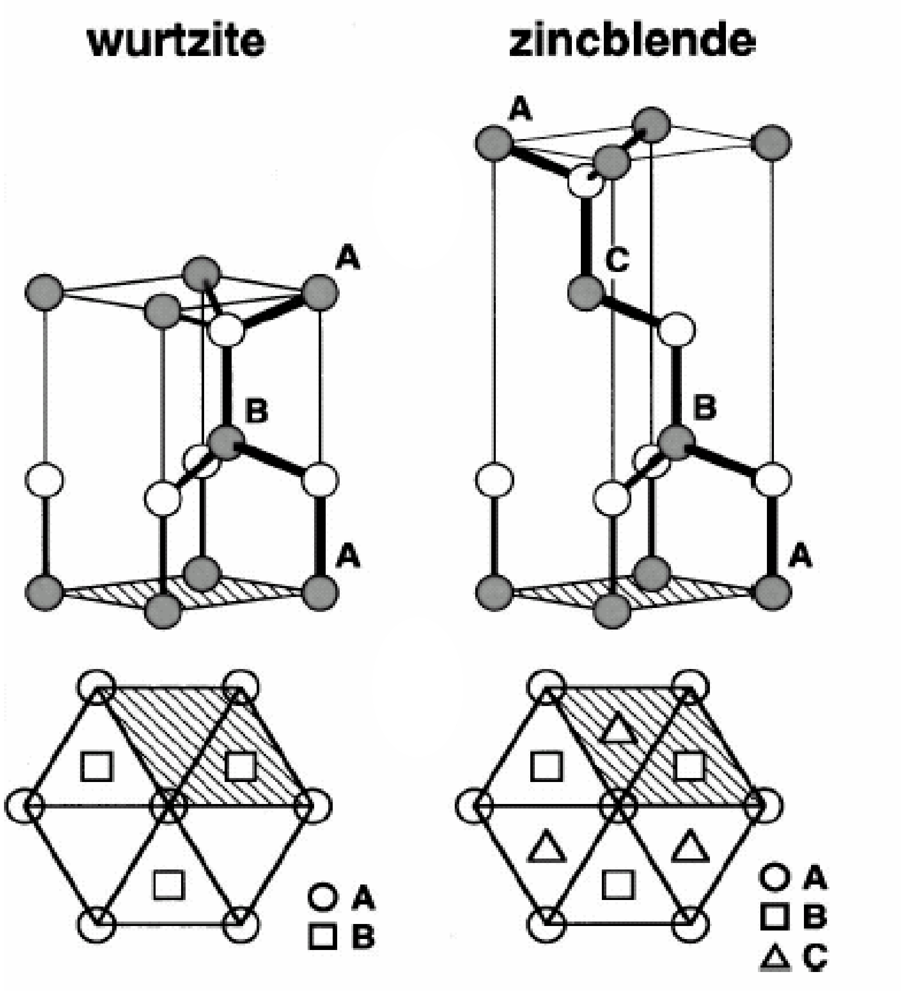
direction of current from crystal axis depends on helicity of beam

known since the 1970s

expect current to be spin-polarized



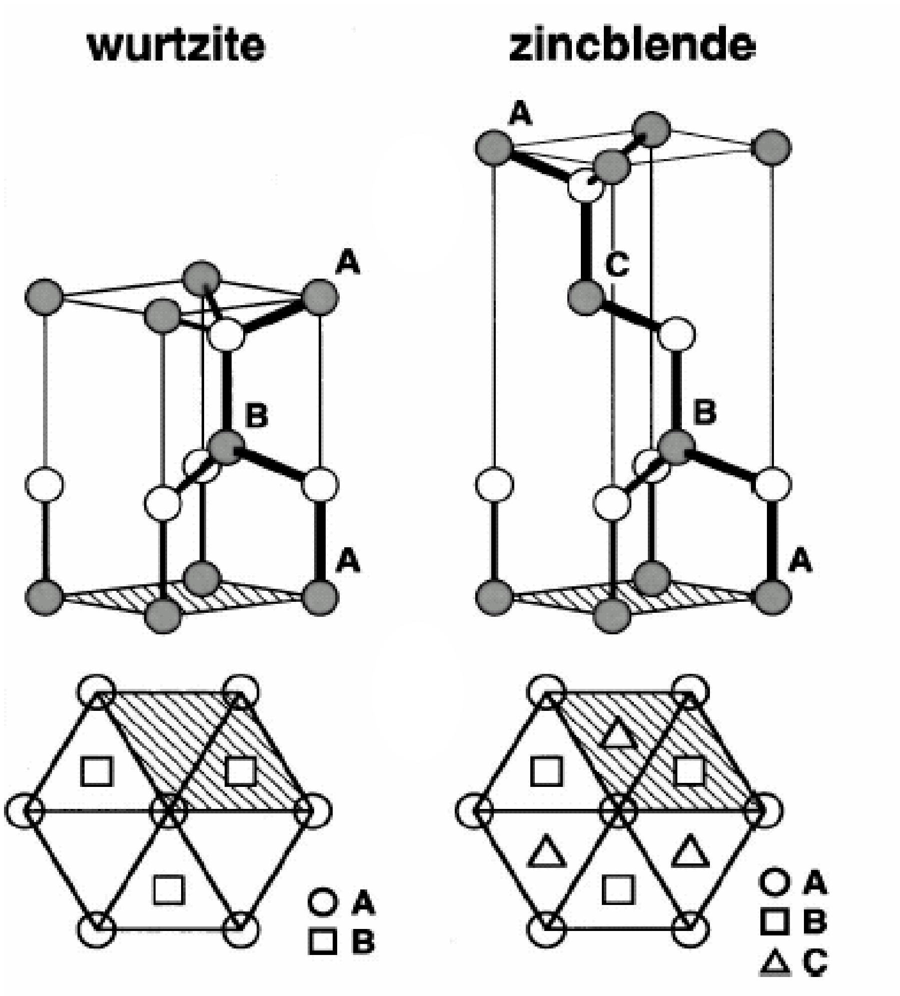
One colour spin-polarized current injection is forbidden in zincblende crystals



but is allowed in wurtzite crystals

Experiment:
N. Laman et al.
Appl. Phys. Lett. ***75****, 2581 (1999)*

One colour spin-polarized current injection is forbidden in zincblende crystals



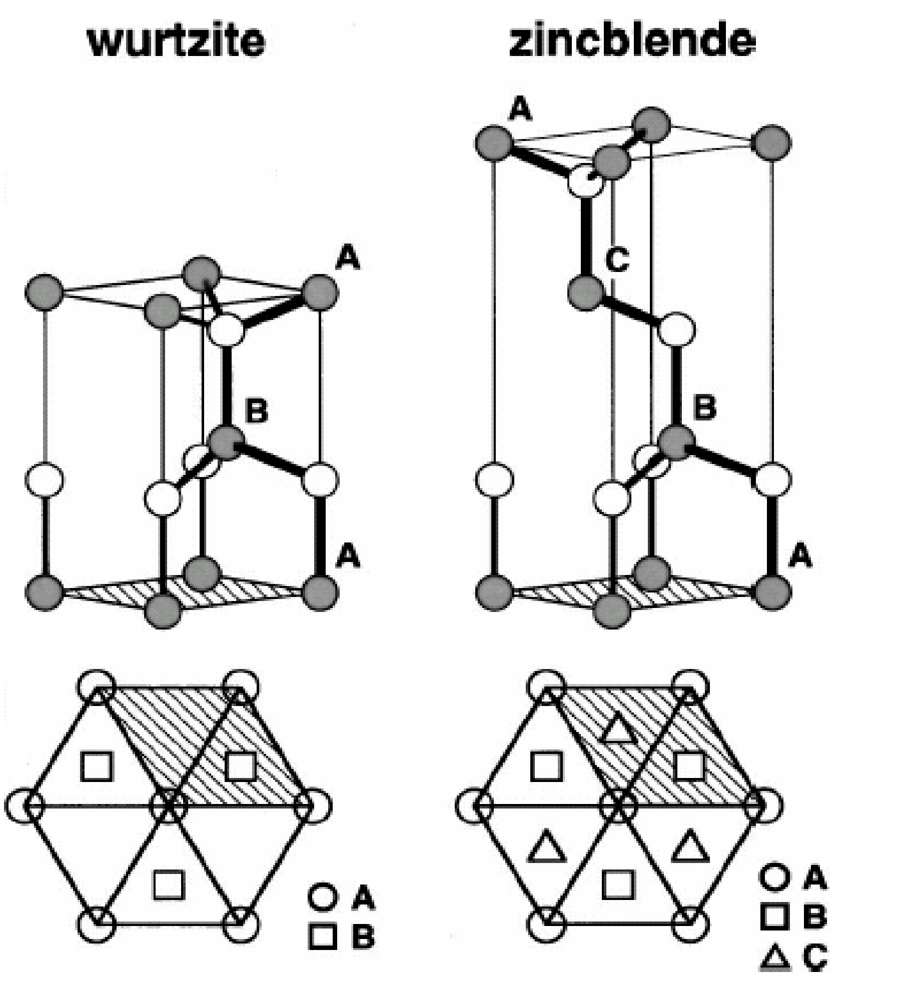
One colour spin-polarized current injection is forbidden in zincblende crystals

but is allowed in wurtzite crystals

Experiment:
N. Laman et al.
Appl. Phys. Lett. ***75****, 2581 (1999)*

…and strained zincblende crystals

Lyanda-Geller and Pikus (1989)



One colour spin-polarized current injection is forbidden in zincblende crystals

but is allowed in wurtzite crystals

Experiment:
N. Laman et al.
Appl. Phys. Lett. **75**, 2581 (1999)

...and strained zincblende crystals

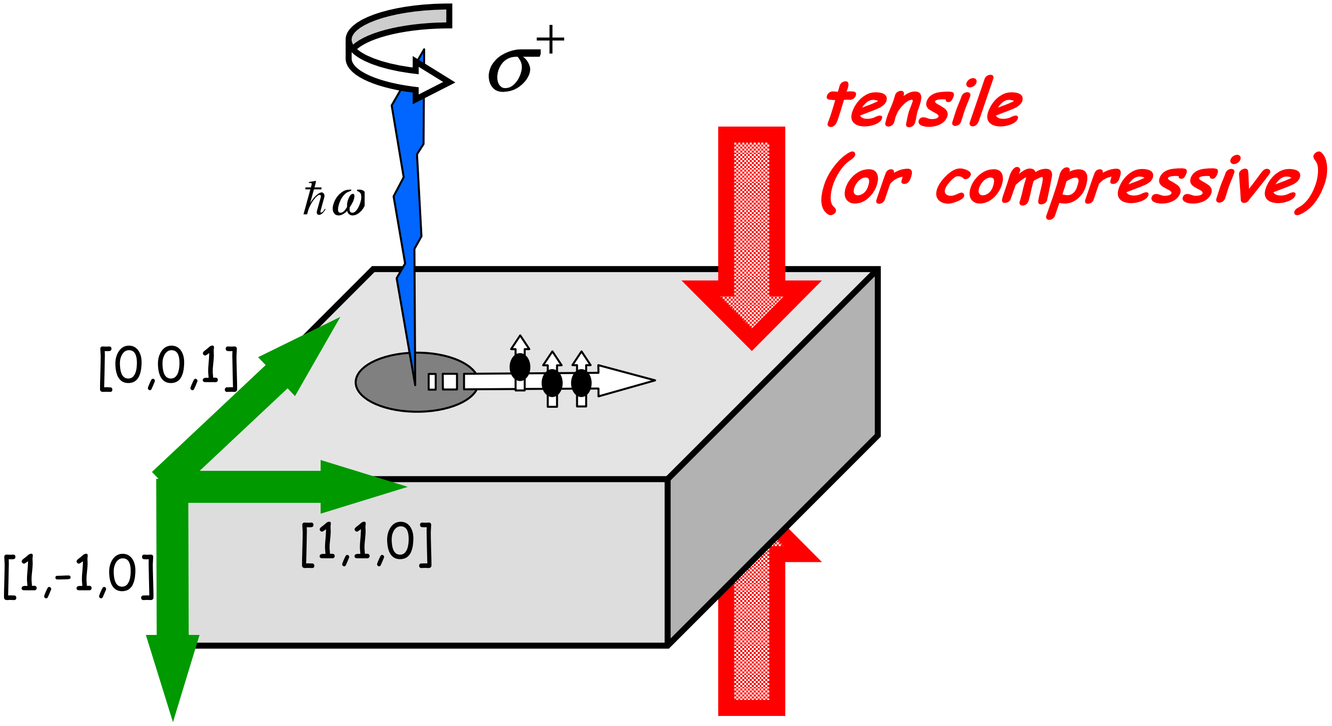
Lyanda-Geller and Pikus (1989)

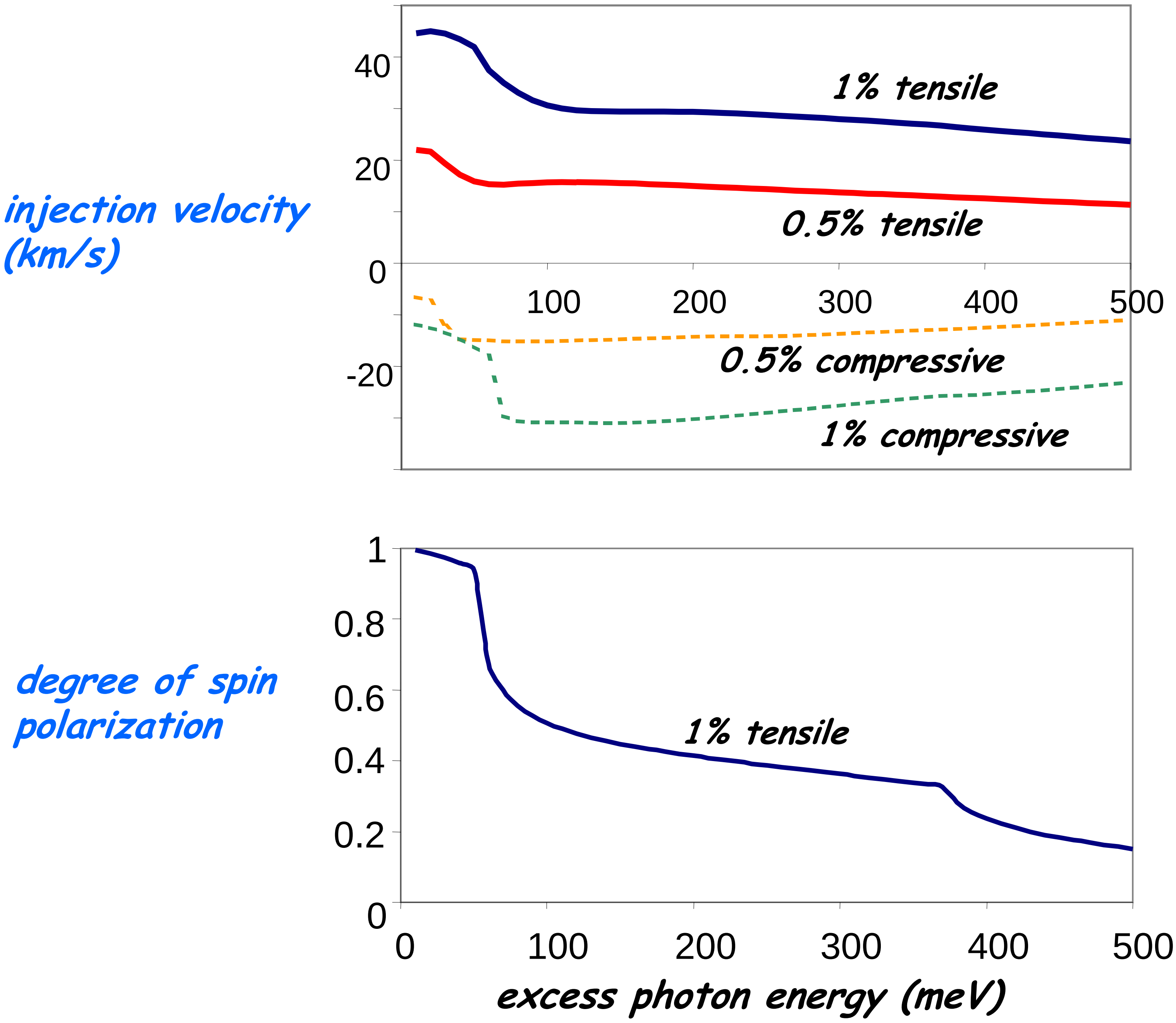
...and GaAs quantum wells

Ganichev et al. (2001)

Golub (2004)

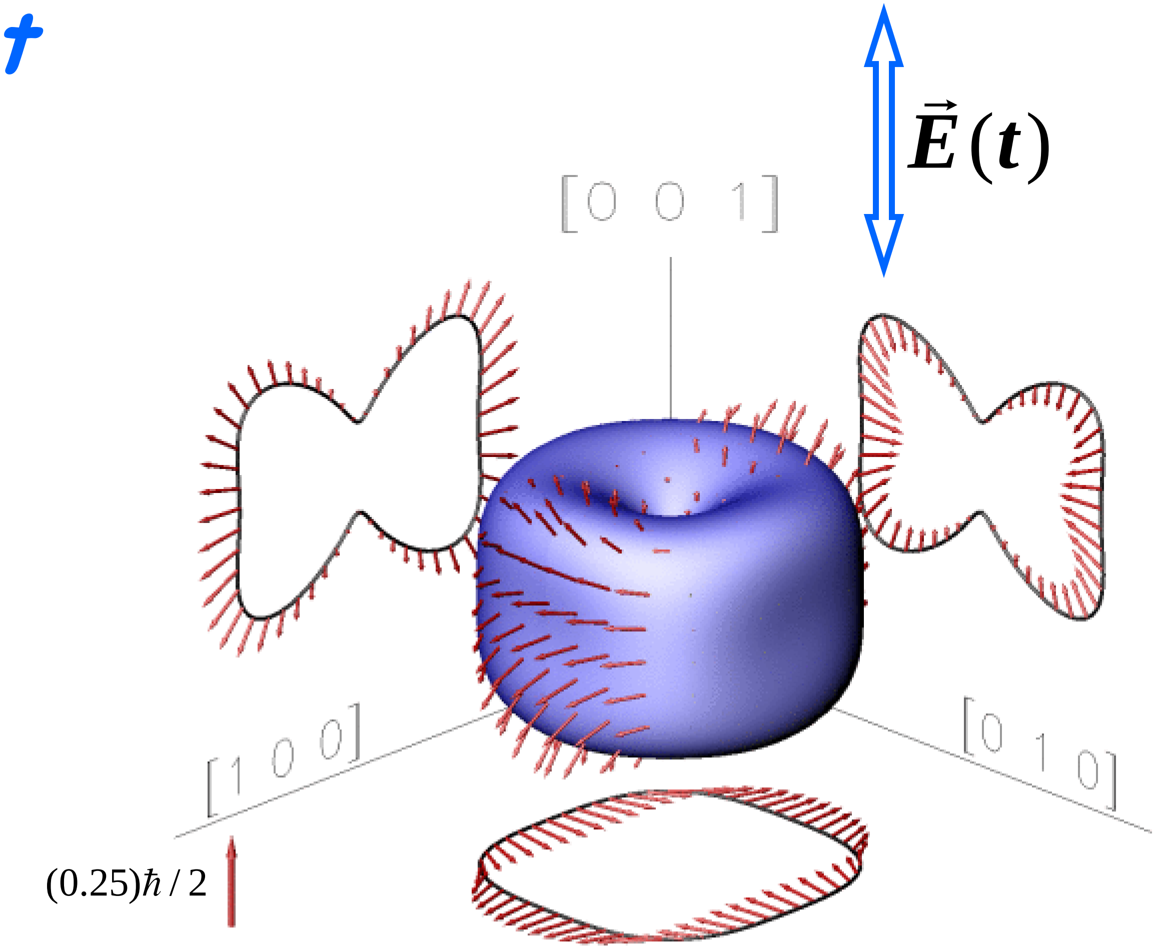
Spin polarized current




injection velocity (km/s)
40
20
0
-20
100
200
300
400
500
1% tensile
0.5% tensile
0.5% compressive
1% compressive
degree of spin polarization
1
0.8
0.6
0.4
0.2
0
0
100
200
300
400
500
1% tensile
excess photon energy (meV)

Pure spin current

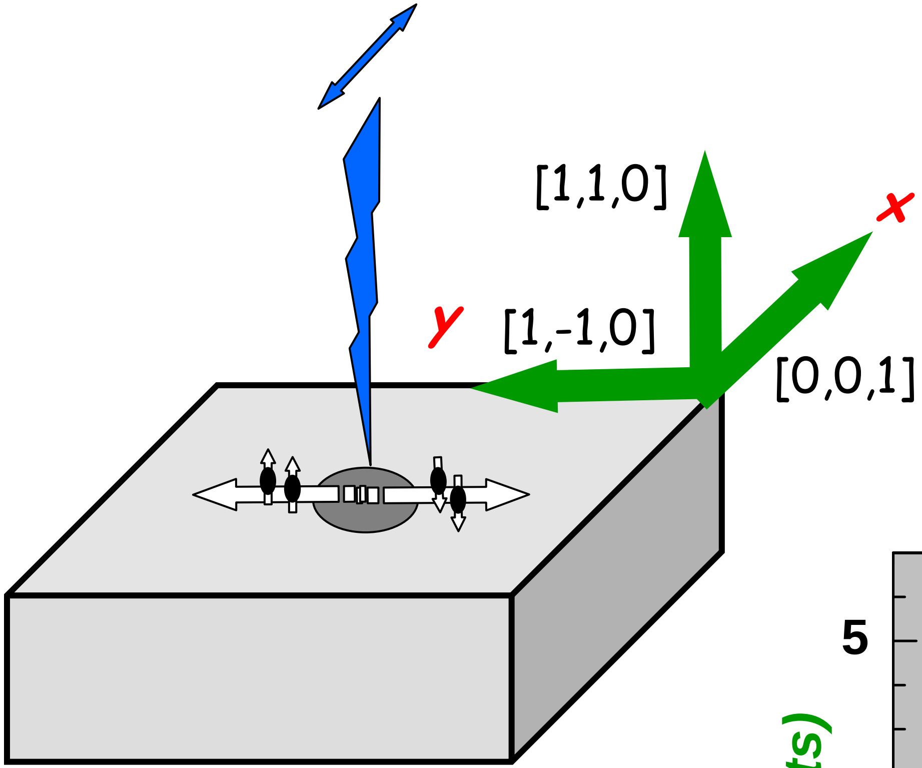
can be injected
by a single beam
even in unstrained,
bulk GaAs !



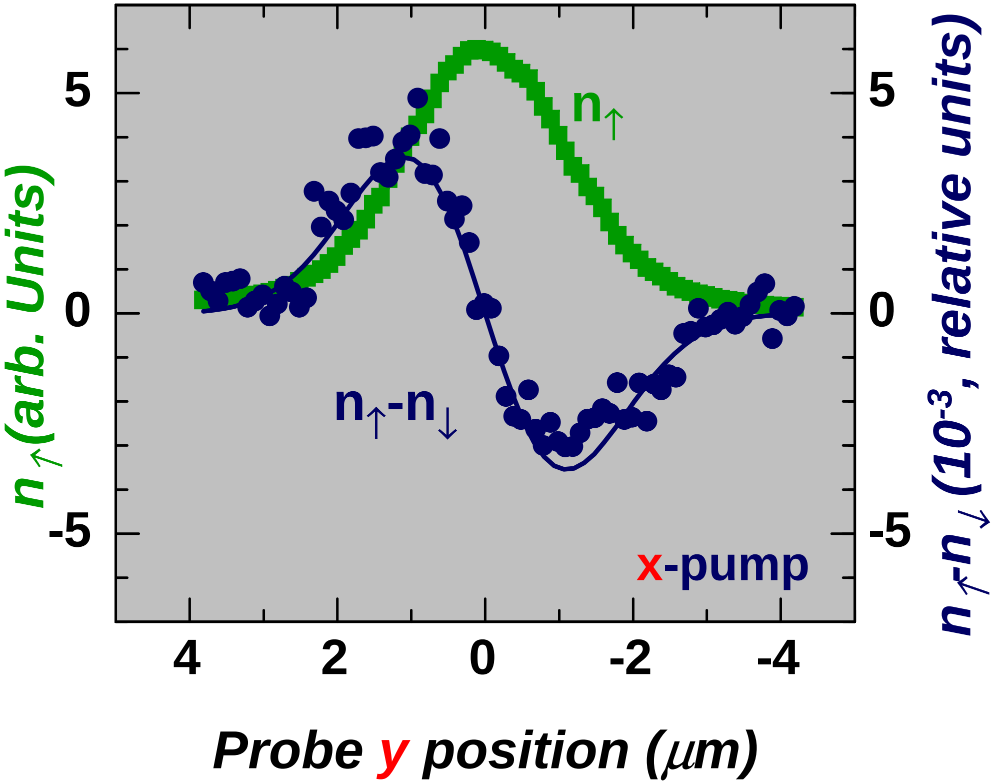
can be understood
as interference
effect between
two circular
components

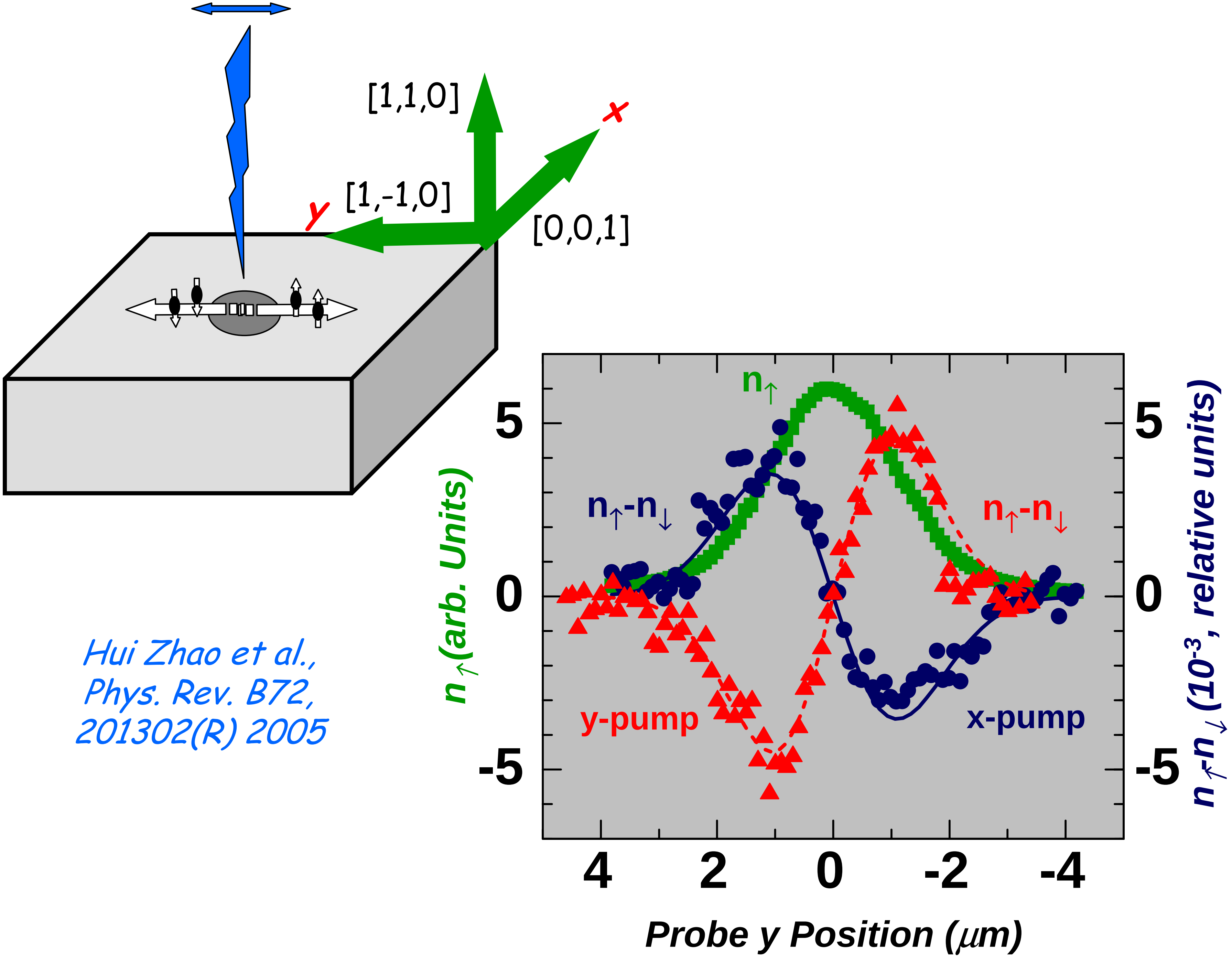
300 meV excess energy

R.D.R. Bhat et al.,
Phys. Rev. Lett. 94,
096603 (2005)



Hui Zhao et al.,
Phys. Rev. B72,
201302(R) 2005

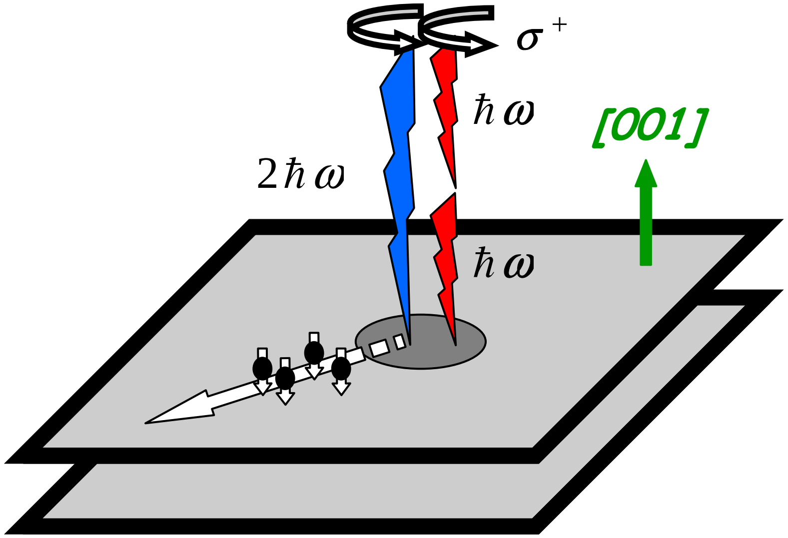


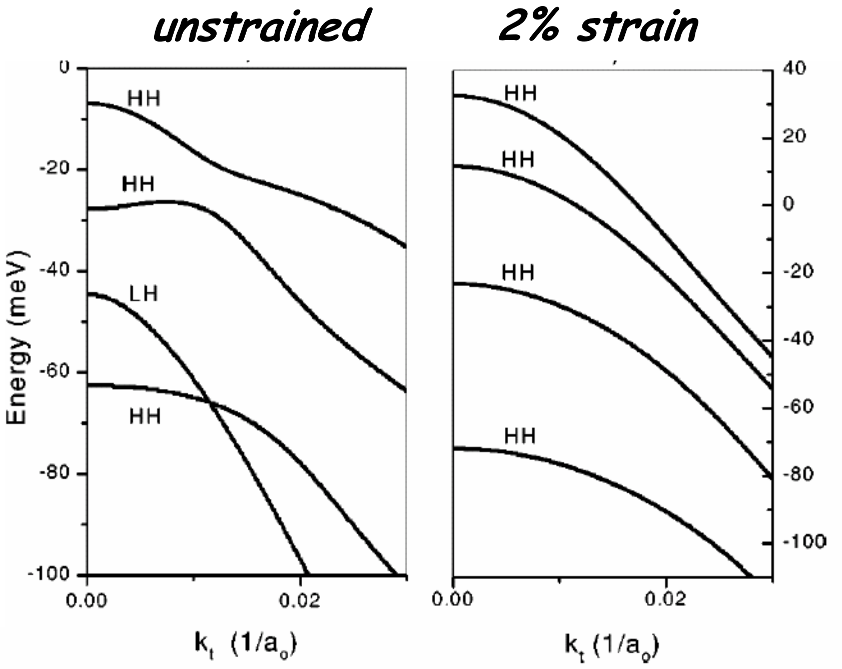


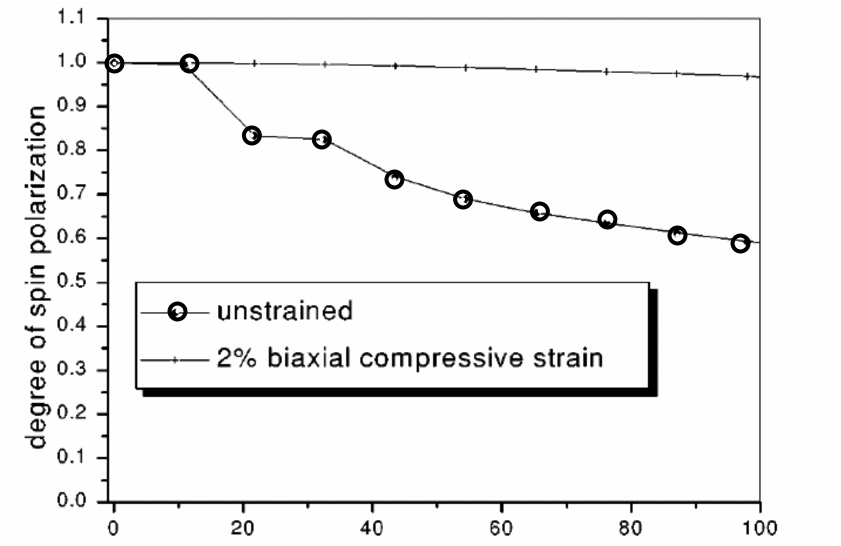
Hui Zhao et al.,
Phys. Rev. B72,
201302(R) 2005

Extensions
and
new schemes

Quantum well geometries



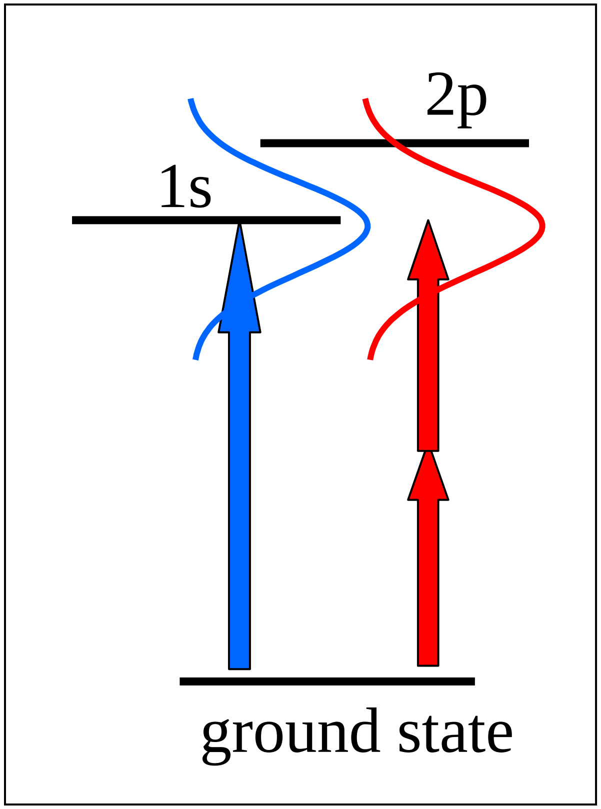


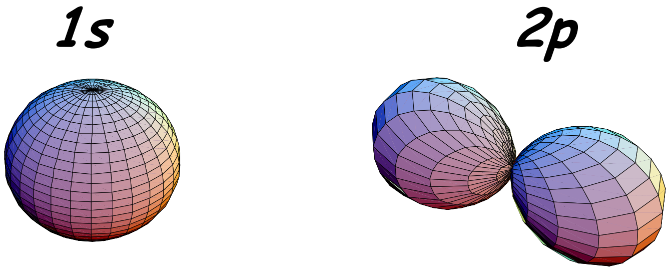


Ali Najmaie et al., Phys. Rev.
***B68**, 165348 (2002)*

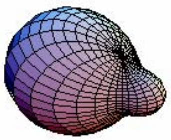
D.H. Marti et al., Phys. Rev.
***B69**, 035335 (2004)*

Coherent control of exciton superpositions





excite a superposition...

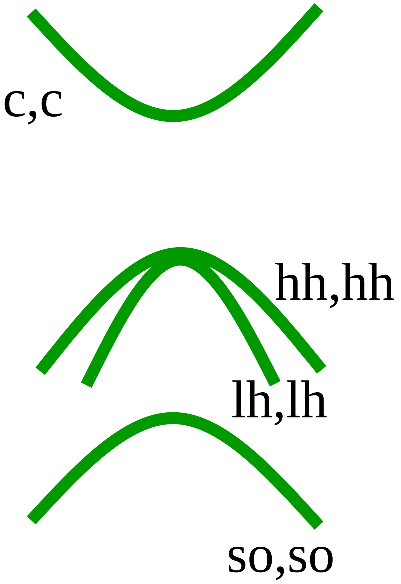


will oscillate in time....

AC currents and
AC pure spin currents !

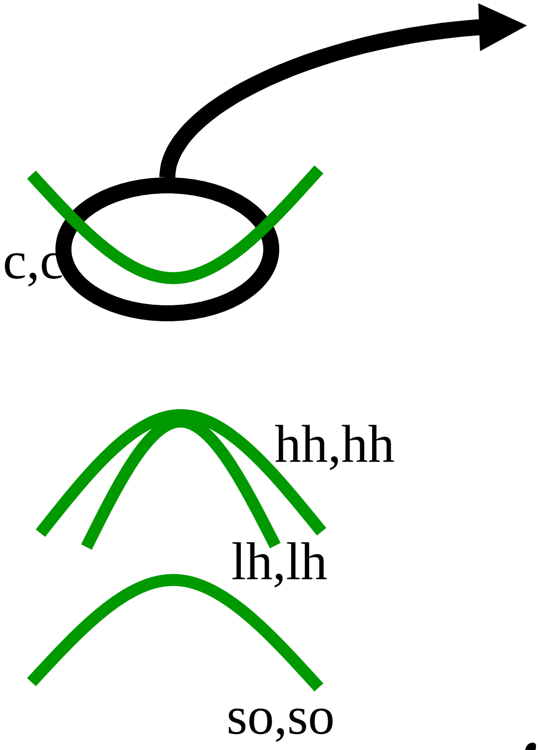
I. Rumyantsev et al.,
submitted to Phys. Rev. B.

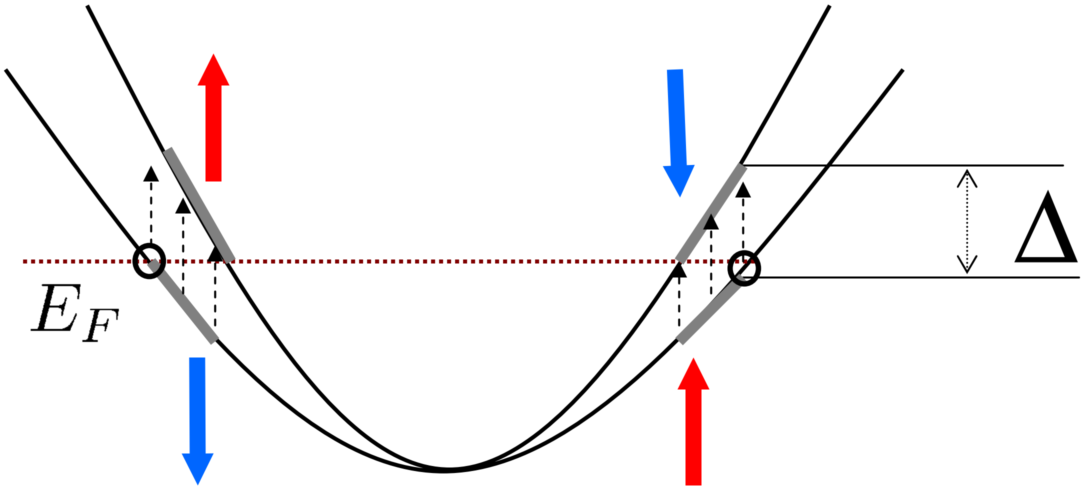
Injecting pure spin current in doped semiconductor structures



Injecting pure spin current in doped semiconductor structures

use spin splitting
of the conduction band

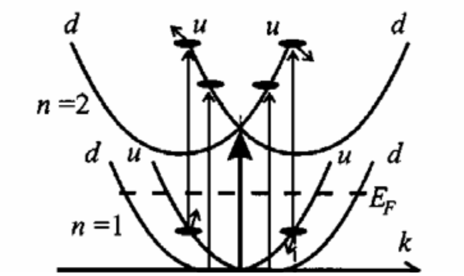




$$\Delta \approx 2\alpha_D k^3 \approx 0.5\ meV$$

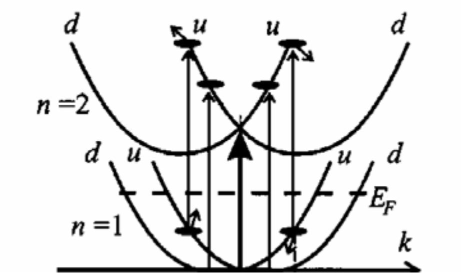
for GaAs with $10^{18}\, cm^{-3}$ free carriers

to inject pure spin current via...



Intersubband absorption in the infrared

*JETP Lett. **81**, 231 (2005)*
*Appl. Phys. Lett. **86**, 122103 (2005)*

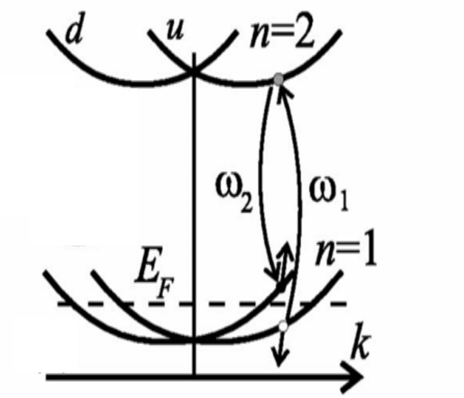


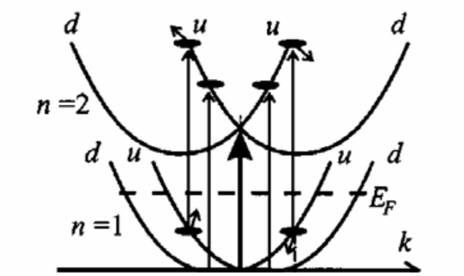
Intersubband absorption in the infrared

JETP Lett. ***81***, *231 (2005)*
Appl. Phys. Lett. ***86***, *122103 (2005)*

Stimulated intersubband Raman scattering in the infrared

Phys. Rev. ***B72***, *041304(R) (2005)*



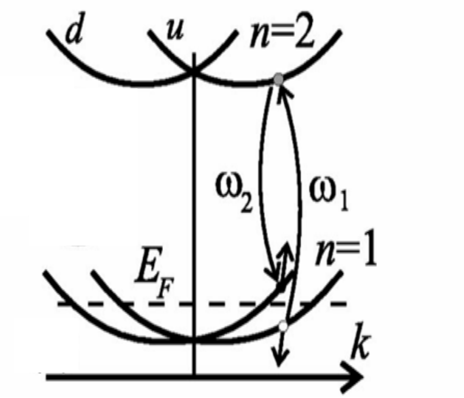


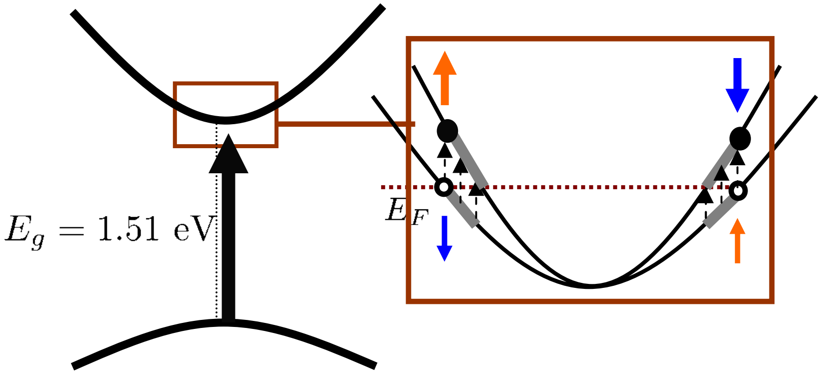
Intersubband absorption in the infrared

JETP Lett. **81**, 231 (2005)
Appl. Phys. Lett. **86**, 122103 (2005)

Stimulated intersubband Raman scattering in the infrared

Phys. Rev. **B72**, 041304(R) (2005)





Stimulated interband Raman scattering in the visible

Phys. Rev. Lett. **95**, 056601 (2005)

A variety of methods for the all-optical injection of currents and spin currents in semiconductors have been proposed and observed in the laboratory.

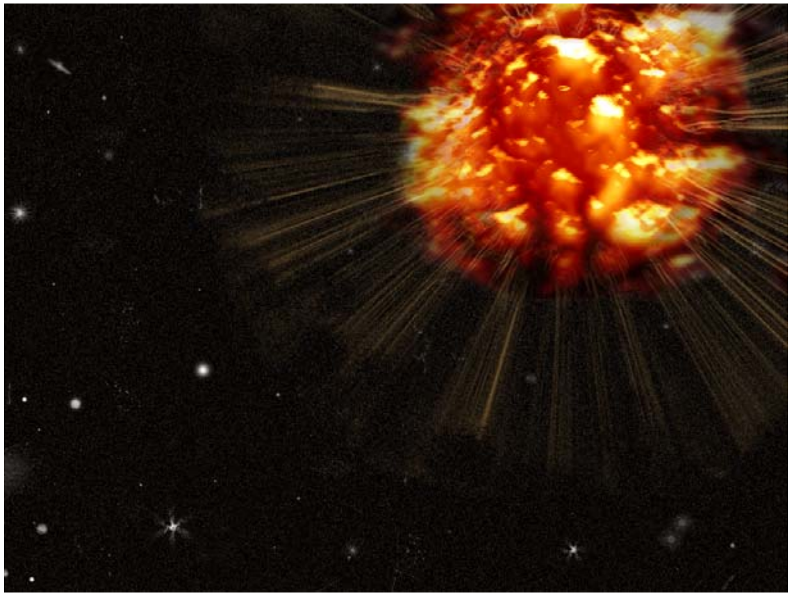
A variety of methods for the all-optical injection of currents and spin currents in semiconductors have been proposed and observed in the laboratory.

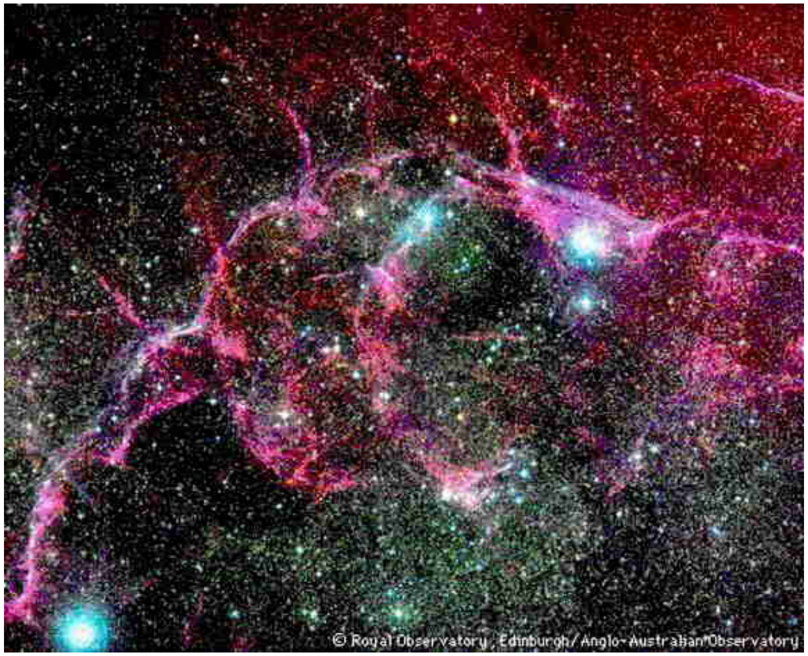
They permit the all-optical creation of novel carrier and spin distributions.

A variety of methods for the all-optical injection of currents and spin currents in semiconductors have been proposed and observed in the laboratory.

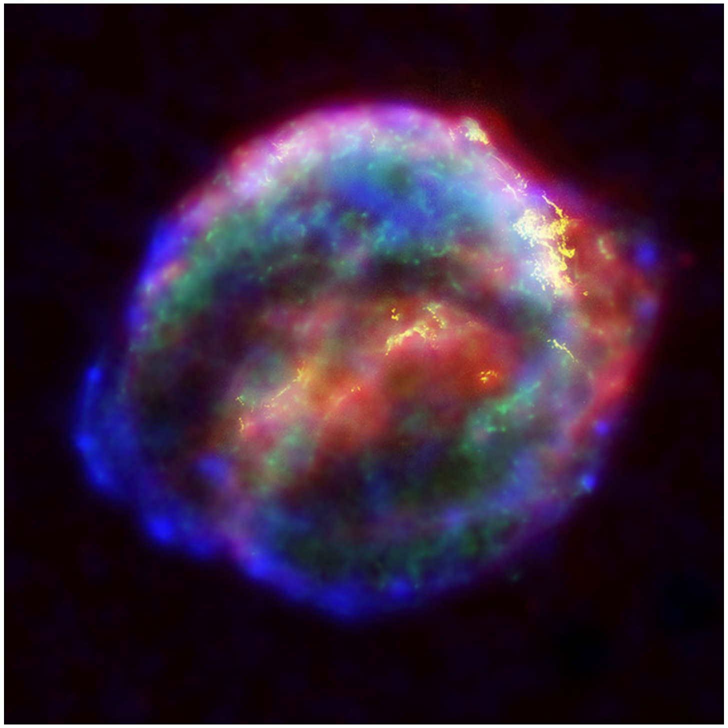
They permit the all-optical creation of novel carrier and spin distributions.

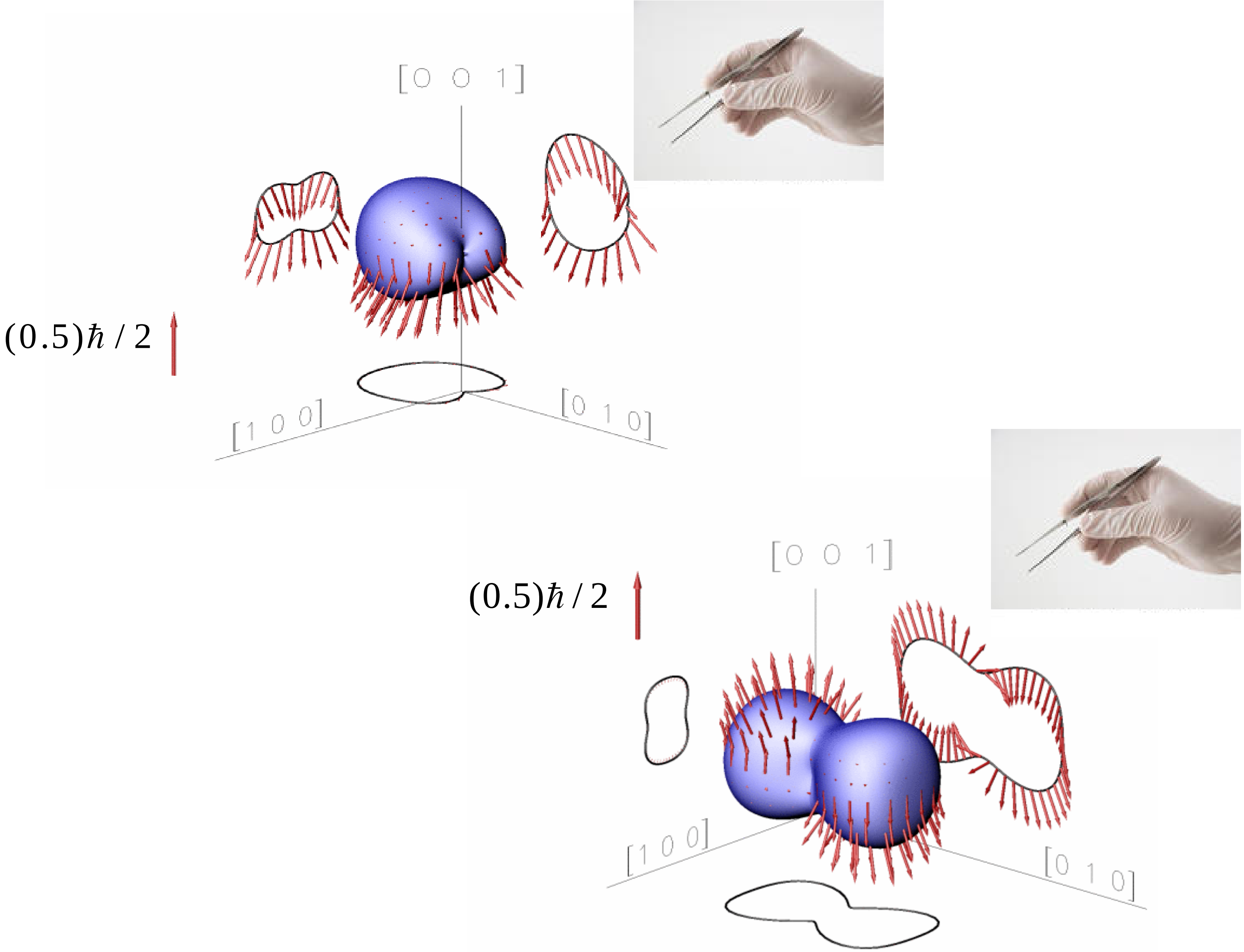
Such scenarios should provide new venues for the study of carrier and spin dynamics in semiconductors.





© Royal Observatory, Edinburgh/Anglo-Australian Observatory




[0 0 1]
(0.5)ℏ / 2
[1 0 0]
[0 1 0]
[0 0 1]
(0.5)ℏ / 2
[1 0 0]
[0 1 0]