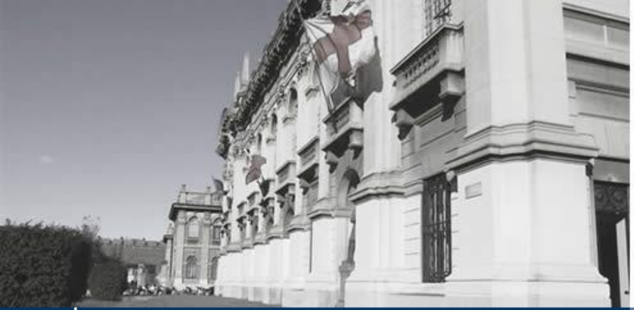


POLITECNICO DI MILANO





Spin properties in Semiconductors

Franco Ciccacci

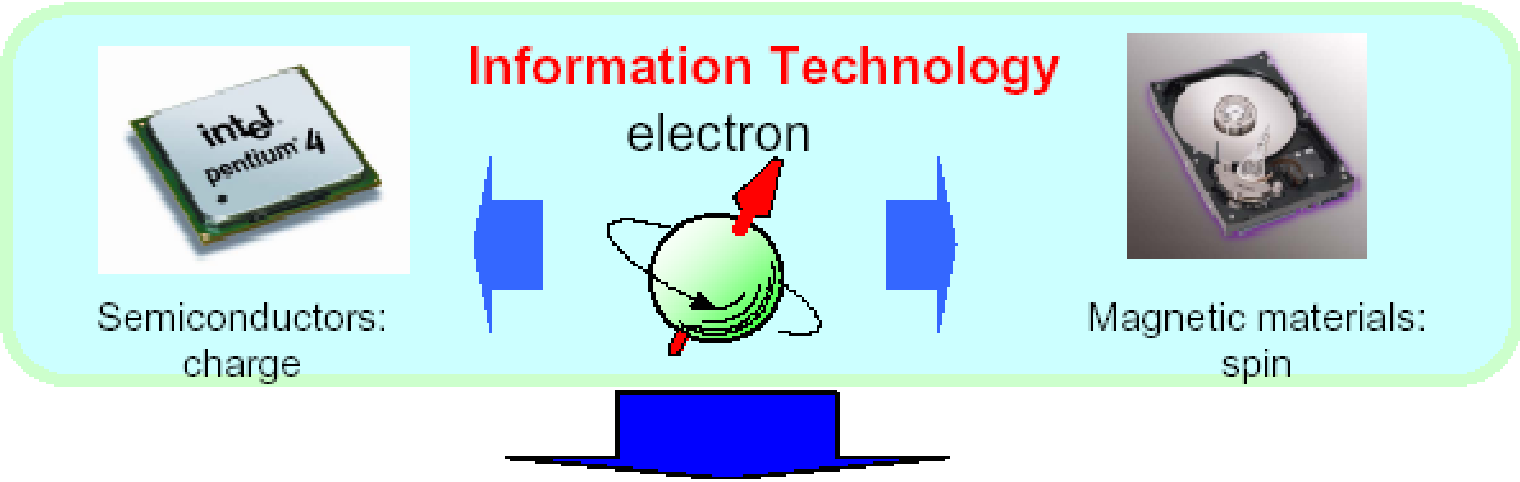
Dipartimento di Fisica – Politecnico di Milano

overview

- introduction
- optical methods (III-V)
- group IV semiconductors (Ge, SiGe)

Spintronics

1988: discovery of Giant Magneto Resistance (A. Fert & P. Grünberg, Nobel prize 2007)



- **adding a new degree of freedom**
- **controlling the carrier spin beside its charge**
- **adding the *spin-up spin-down* magnetic dualism to the conventional electron hole dualism**
- **combining small scale (nanometric) magnetic elements with conventional semiconductor electronics**

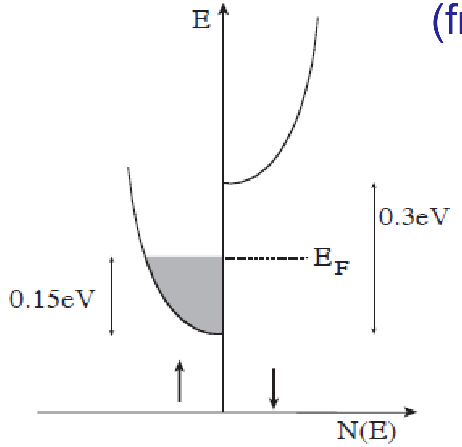
magnetic AND semiconducting properties

"the search for material-combining properties of the ferromagnet and the semiconductor has been a long-stranding and elusive goal …"

Jianbai Xia, Weikun Ge, Kai Chang: ***Semiconductor Spintronics*** (World Scientific, Singapore 2012)

magnetic AND semiconducting properties

FS: Ferromagnetic Semiconductors (from '60s)



e.g.: EuS → $\mathbf{T_C}$ ~ Liquid He

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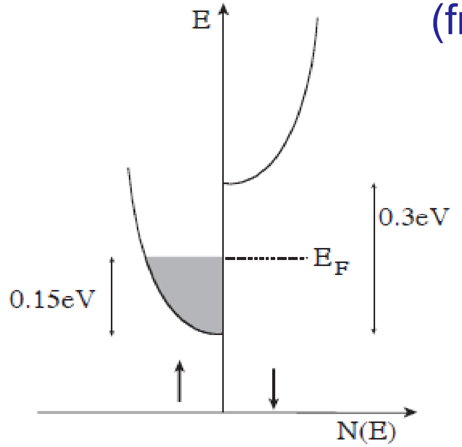

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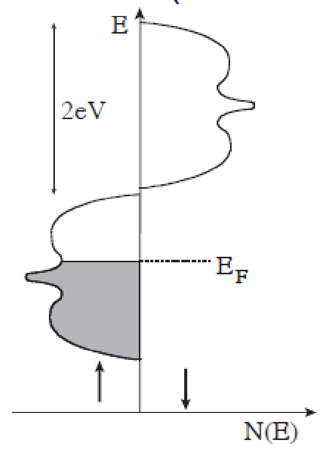
Half metals (from '90s)



CrO_2 , $La_{0.7}$ $Sr_{0.3}MnO_3$, NiMnSb, Fe_3O_4 **T_C** > RT

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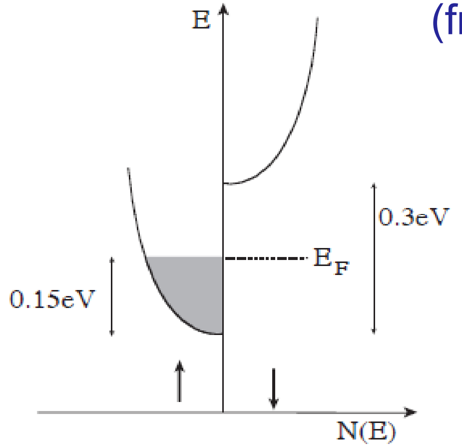

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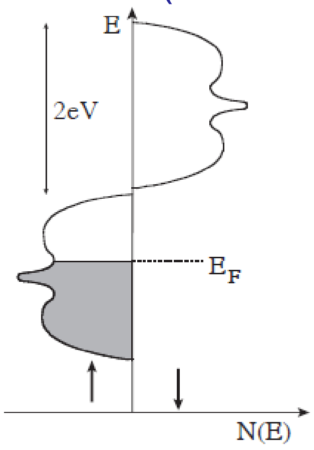

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CrO_2 , $La_{0.7}Sr_{0.3}MnO_3$, NiMnSb, Fe_3O_4 $\mathbf{T_C}$ > RT

DMS: diluted magnetic semiconductors

Mn-doped GaAs → $\mathbf{T_C}$ ~ 110 K

H. Ohno *et al.*, *Appl. Phys. Lett.* 69, 363 (1996).

H. Ohno *et al.*, *Nature* 408, 944 (2000).

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magnetic AND semiconducting properties

Alternative routes:

- Spin Injection form Ferromagnetic Metal (FM) into Semiconductor (SC)

- Optical spin orientation (optical pumping)

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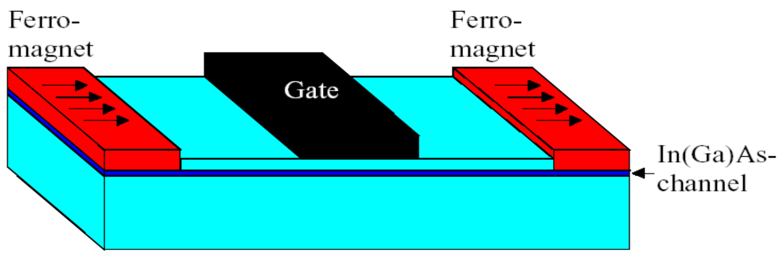
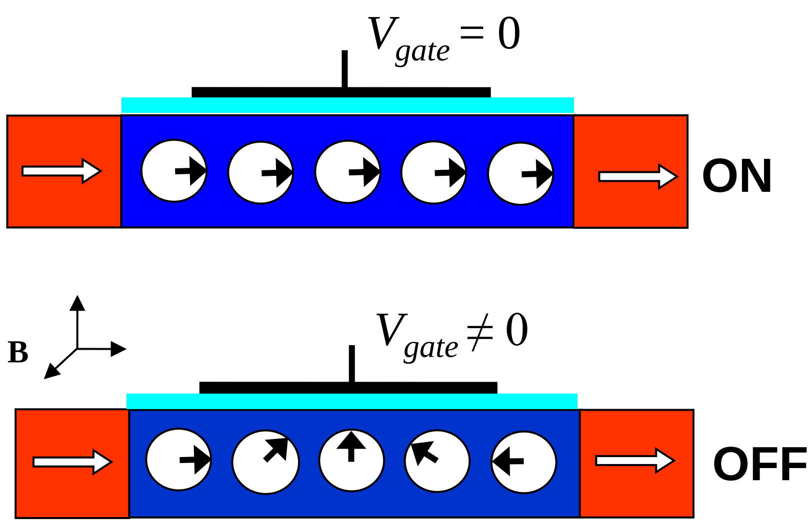
Spin-FET



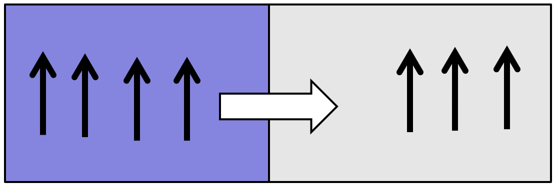
Spin modulation by gate voltage (spin-orbit effect)



S. Datta and B. Das, Appl. Phys. Lett., 56, 665 (1990)

Electrical Spin injection

FM → NM



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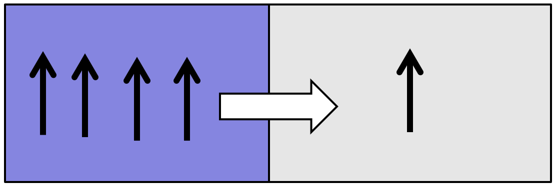
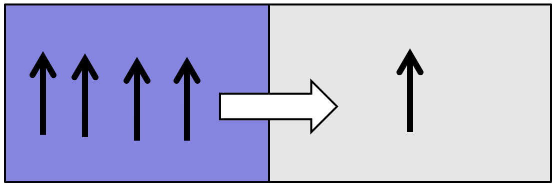


1st Problem: ohmic contact

(P < 5% at T<10K)

Electrical Spin injection

FM → NM



σ_{FM} σ_{NM}

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(P < 5% at T<10K)

Fundamental problem: *"conductivity mismatch"*

G. Schmidt et al., Phys. Rev. B 62, R4790 (2000)
A. Fert and H. Jaffrés, Phys. Rev. B, 184420 (2001)

$\sigma_{FM} \leq \sigma_{NM}$ ☺

$\sigma_{FM} > \sigma_{NM}$ ☹

Electrical Spin injection

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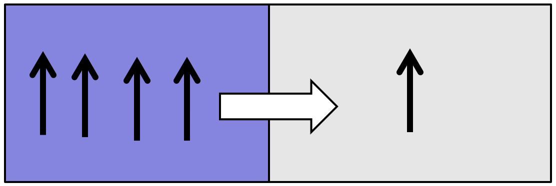

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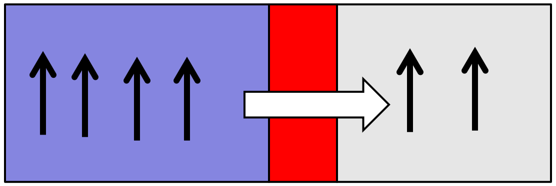
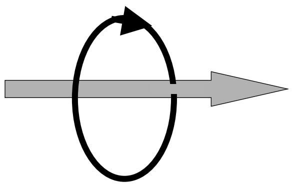
→ Tunneling junction



Fe/MgO/GaAs

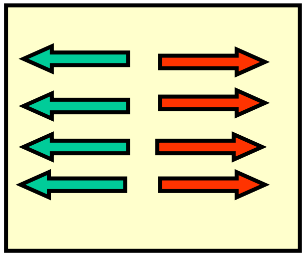
Optical Pumping

radiation to matter transfer of angular momentum



circularly polarized light

spin 1

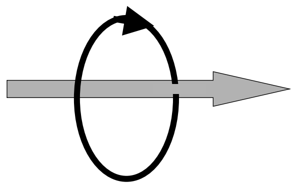


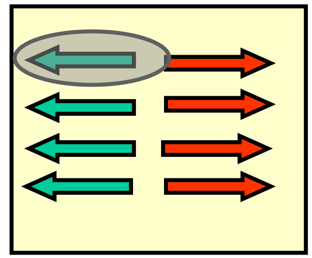
non magnetic material

spin $+\frac{1}{2}$ e $-\frac{1}{2}$

Optical Pumping

radiation to matter transfer of angular momentum





circularly polarized light

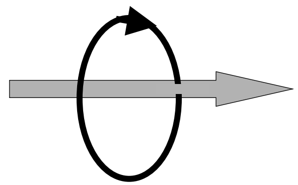
spin 1

non magnetic material

spin + ½ e − ½

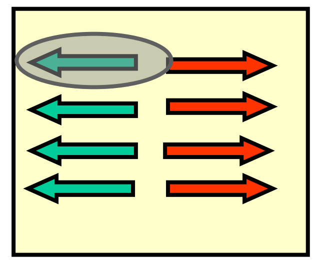
Optical Pumping

radiation to matter transfer of angular momentum



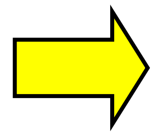
circularly polarized light

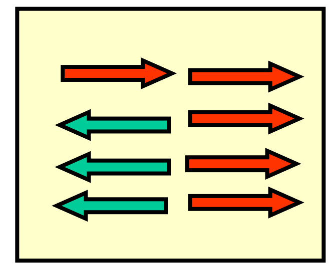
spin 1



non magnetic material

spin + ½ and – ½

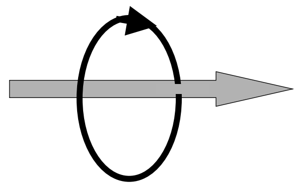


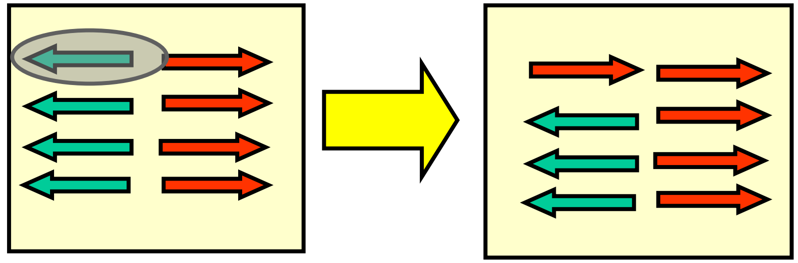


after absorption

polarization

radiation to matter transfer of angular momentum





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In semiconductors:

George Lampel 1968 *Phys. Rev. Lett.* **20**, 491

VOLUME 20, NUMBER 10 PHYSICAL REVIEW LETTERS 4 MARCH 1968

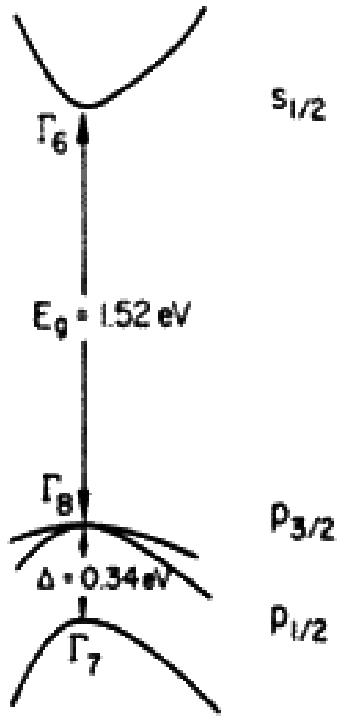
NUCLEAR DYNAMIC POLARIZATION BY OPTICAL ELECTRONIC SATURATION AND OPTICAL PUMPING IN SEMICONDUCTORS*

Georges Lampel
Ecole Polytechnique,† Paris, France
(Received 12 December 1967)

A nonresonant Overhauser effect by photoexcited conduction electrons is obtained on Si^{29} nuclei in silicon at 77°K in two different ways: (a) Saturation of the electronic magnetization is achieved with unpolarized light by exciting an equal number of spins up and spins down. (b) Polarized electronic spins are produced by optical pumping with circularly polarized light; the nuclear magnetization obtained in 1 G by optically pumped electrons corresponds to the equilibrium value at 77°K in 28 kG.

III-V direct gap semiconductors

GaAs



review: F. Meier, B.P. Zakharchenya, *Optical orientation,* North Holland, Amsterdam, 1984

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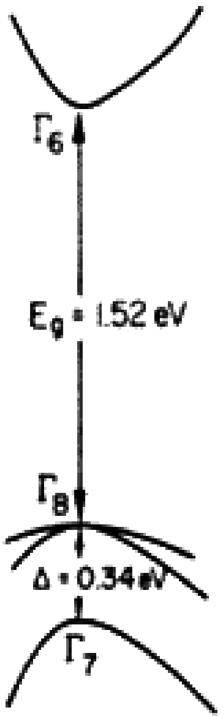

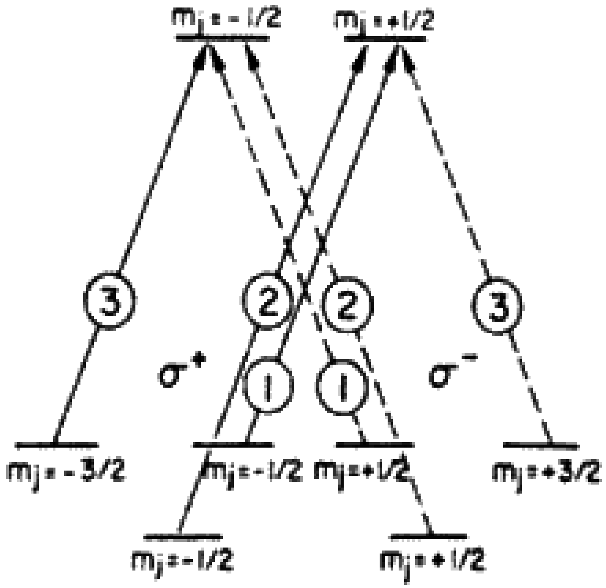

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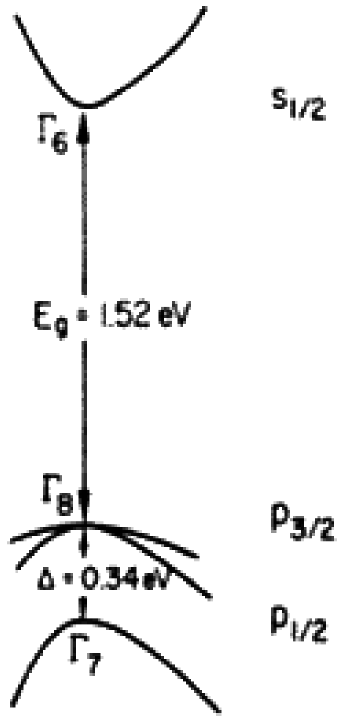
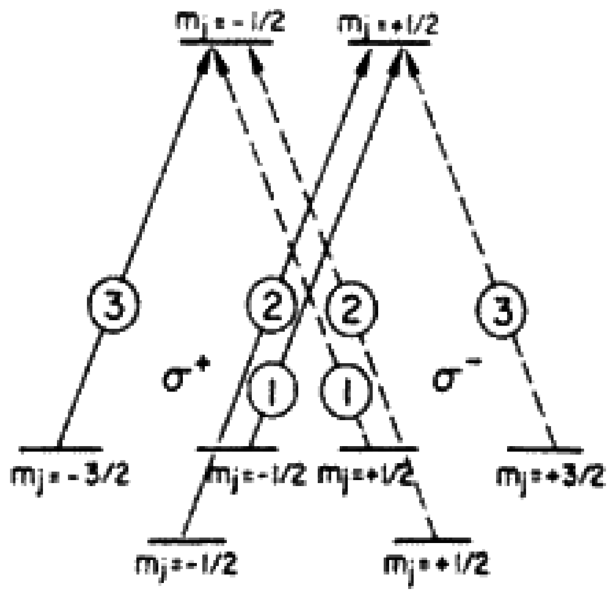
band-gap excitation

$h\nu = E_g$





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III-V direct gap semiconductors

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$$P = \frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow} = \frac{3-1}{3+1}$$

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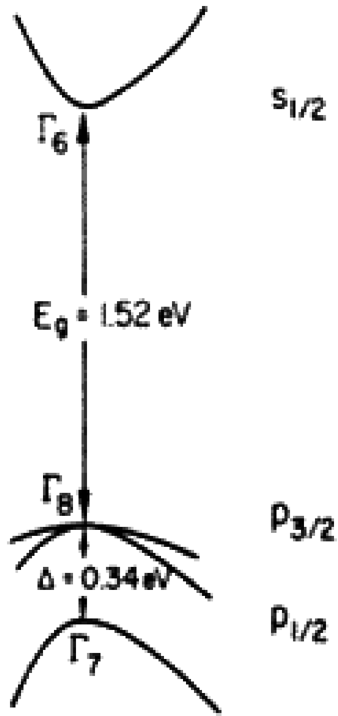

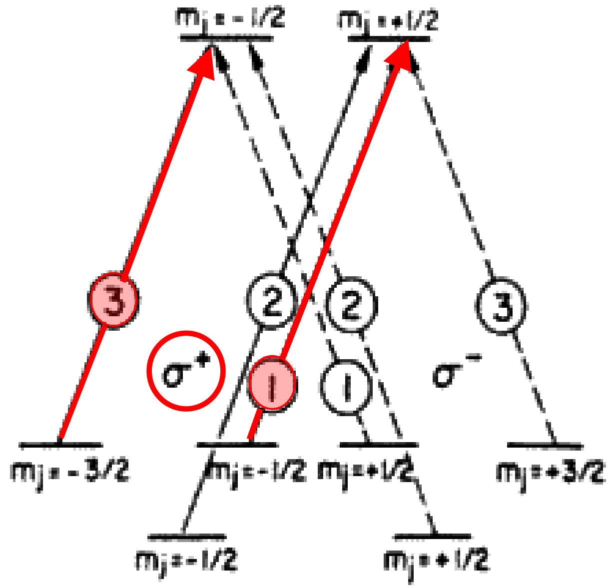

$\sigma^+ : \Delta m_j = +1$ ➡ $P = -50\%$

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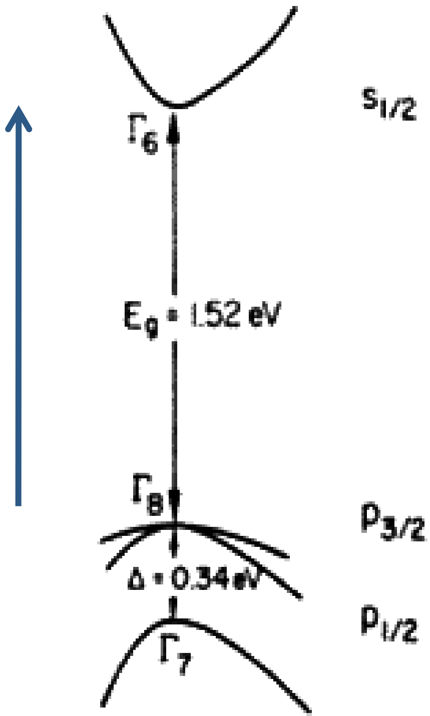

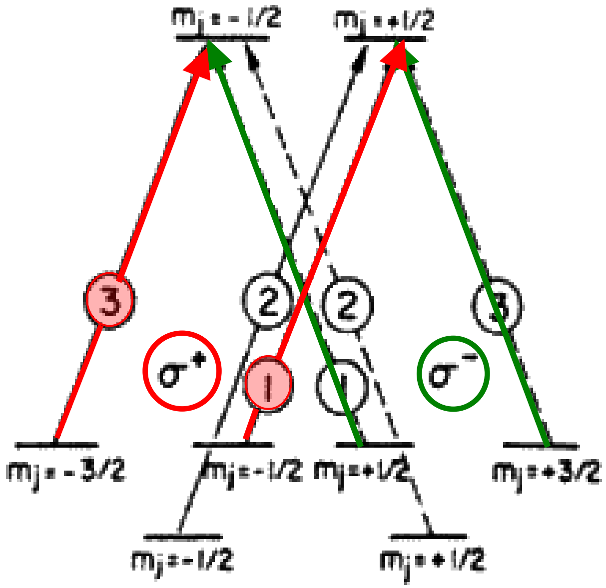

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$\sigma^- : \Delta m_j = -1$ ➡ $P = +50\%$

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Polarized photo-luminescence

VOLUME 23, NUMBER 20 PHYSICAL REVIEW LETTERS 17 NOVEMBER 1969

BAND-TO-BAND OPTICAL PUMPING IN SOLIDS AND POLARIZED PHOTOLUMINESCENCE

R. R. Parsons*
…technique, 17 rue Descartes Paris Ve,† France
(Received 29 September 1969)

GaSb

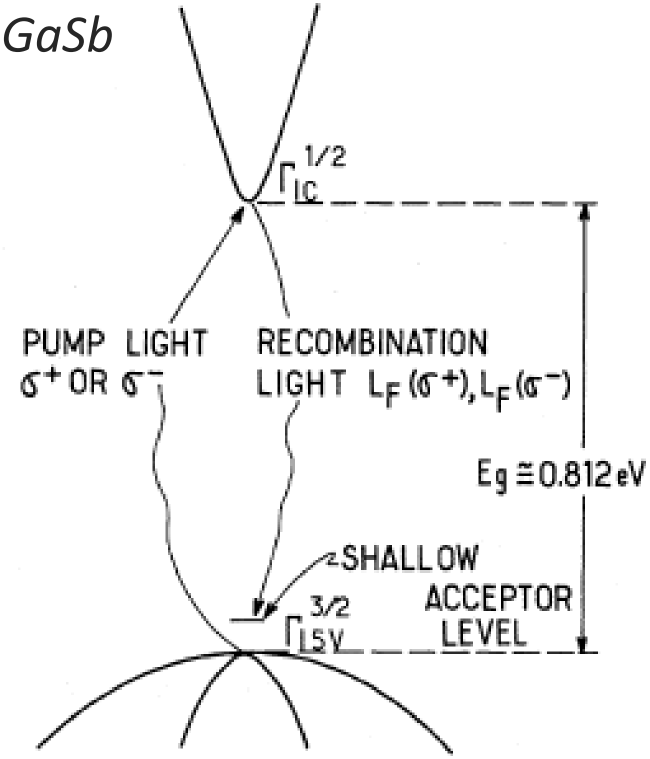

FIG. 1. The optical pumping cycle: excitation across the band gap with σ^+ or σ^- pump light, spin relaxation of the photocreated $\Gamma_{1c}^{1/2}$ electrons, and recombination emission involving shallow acceptor states. $L_F(\sigma^\pm)$ is the intensity of the photoluminescence of polarization $\sigma^\pm$.

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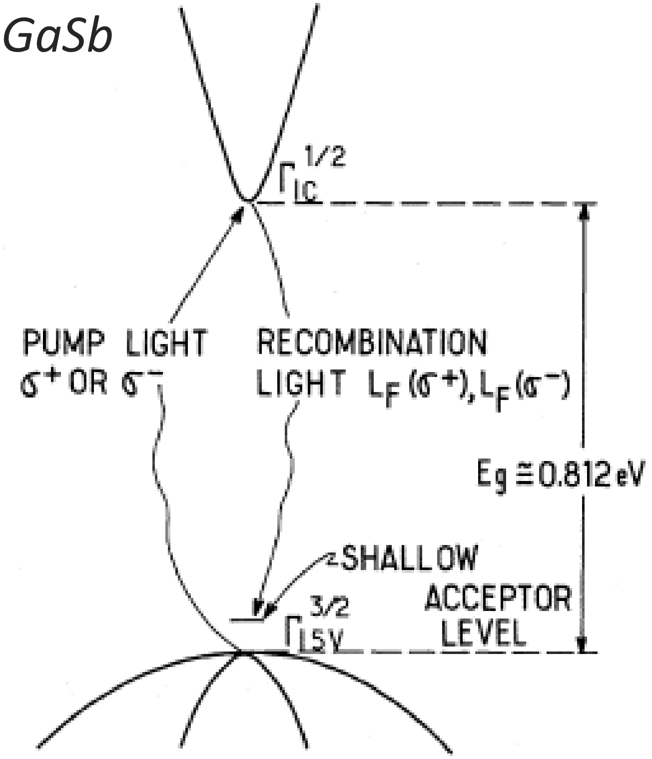

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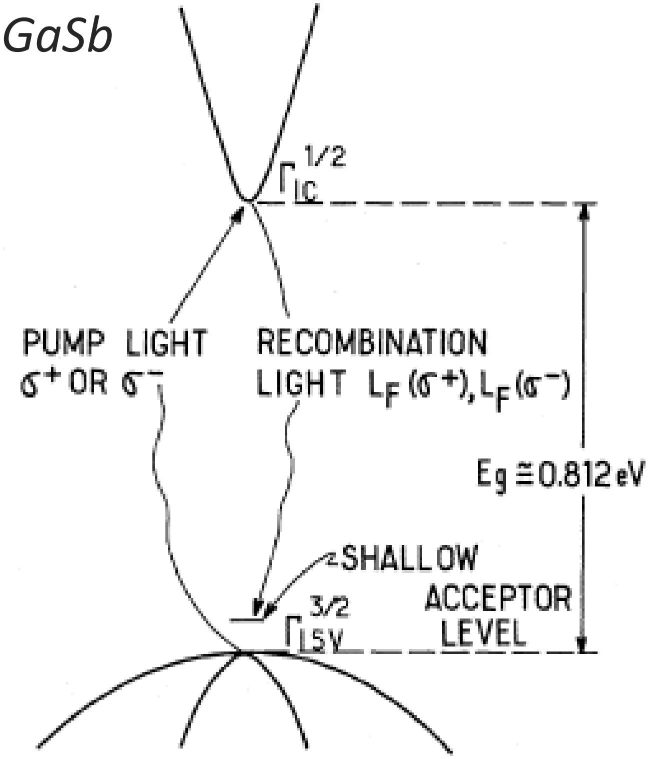

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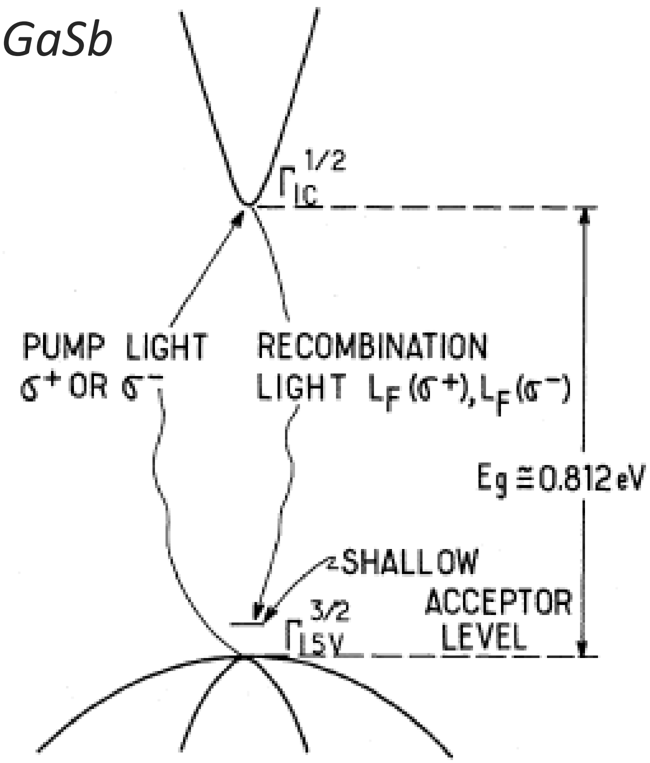

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Polarized photo-luminescence

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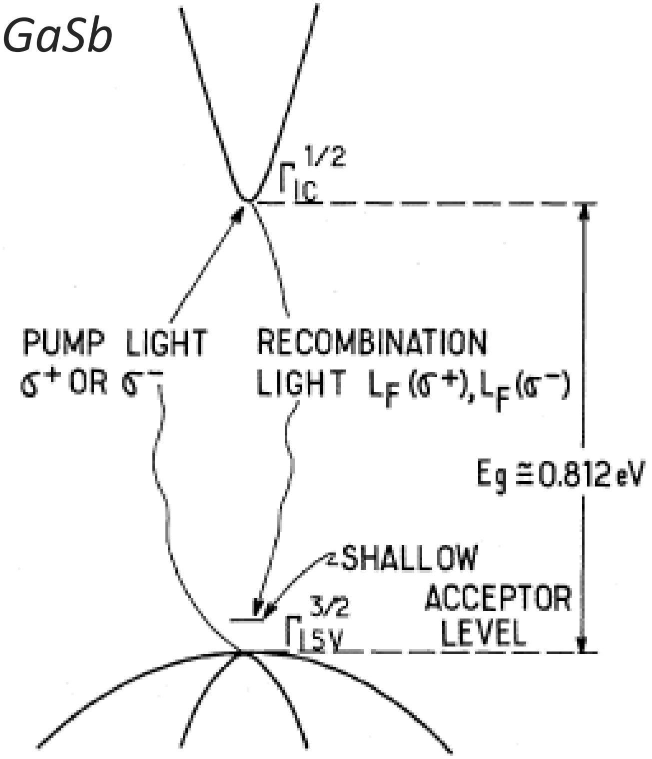

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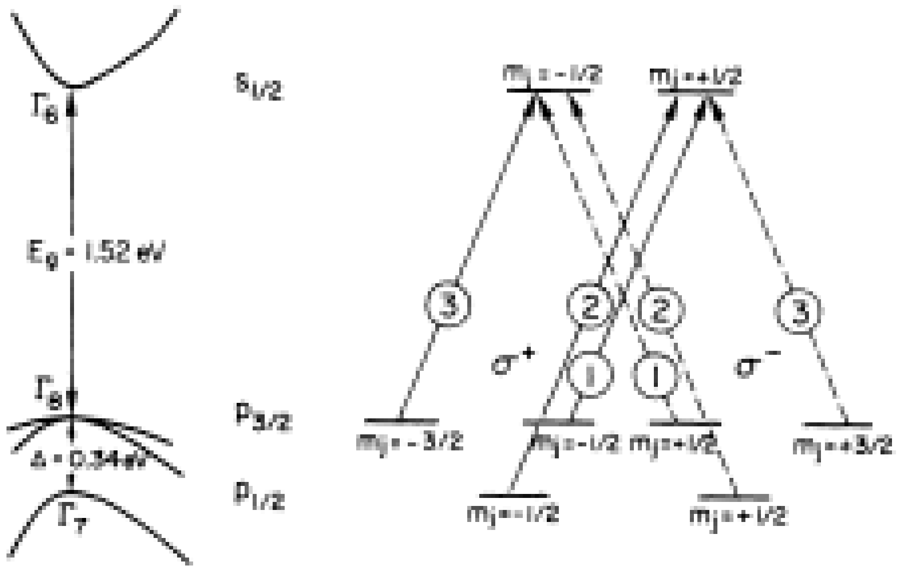
$$\rho = P\left|(r_+ - r_-)/(r_+ + r_-)\right|.$$

$\rho = 0.21\ (\pm 0.04)$, we obtain $P = 42\ (\pm 8)\ \%$.

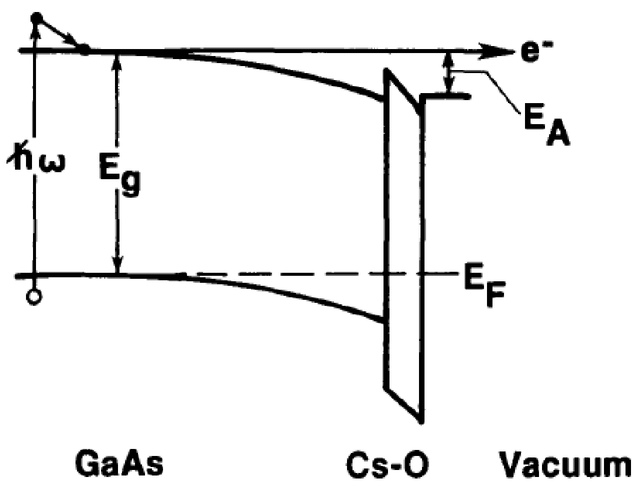
Spin polarized photoemission

Optical pumping



+

Negative Electron Affinity



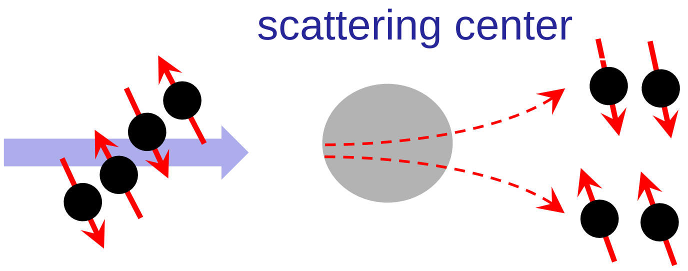
electrons emitted in vacuum:

can we measure their spin polarization?

Mott scattering

Electron scattering with Spin-Orbit interaction

Spin dependent left-to-right asymmetry



more effective in materials with heavy atoms (strong Z-dependence)

Mott scattering

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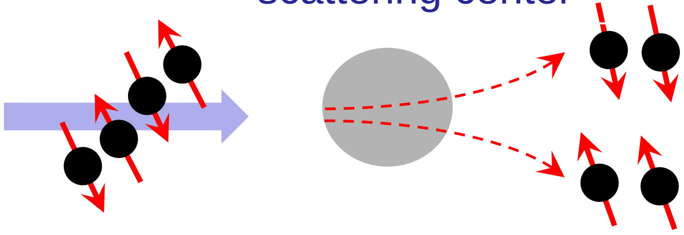

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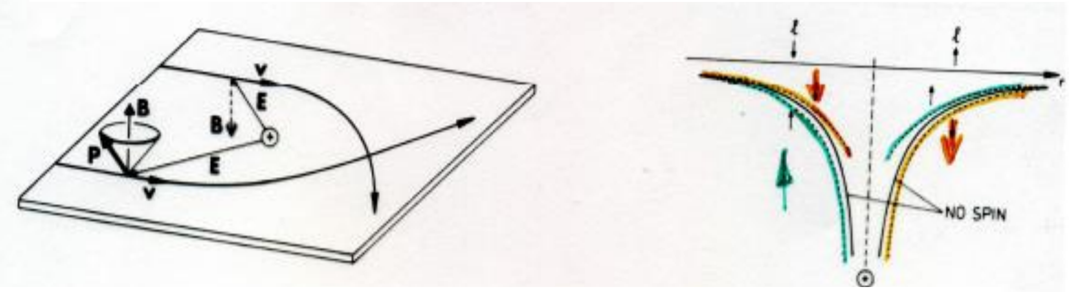
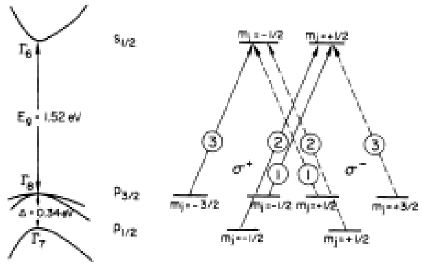


at high energy

electron scattering from atomic nucleus: Rutherford + Spin-Orbit

cross section: Sherman function

Spin polarized photoemission: NEA GaAs



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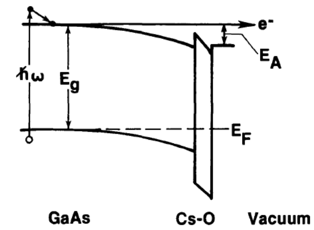
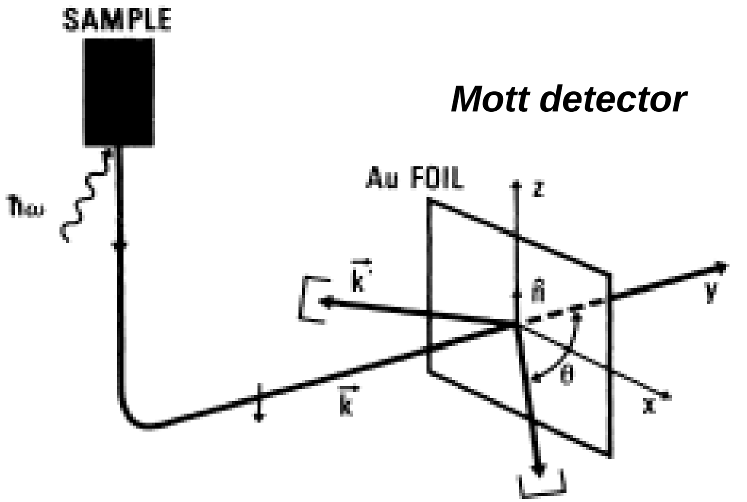


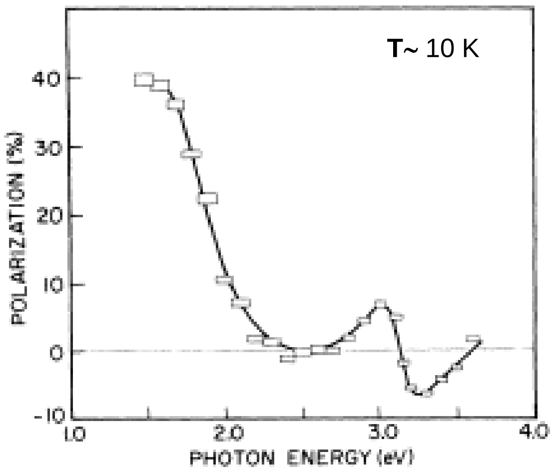
PHYSICAL REVIEW B VOLUME 13, NUMBER 12 15 JUNE 1976

Photoemission of spin-polarized electrons from GaAs

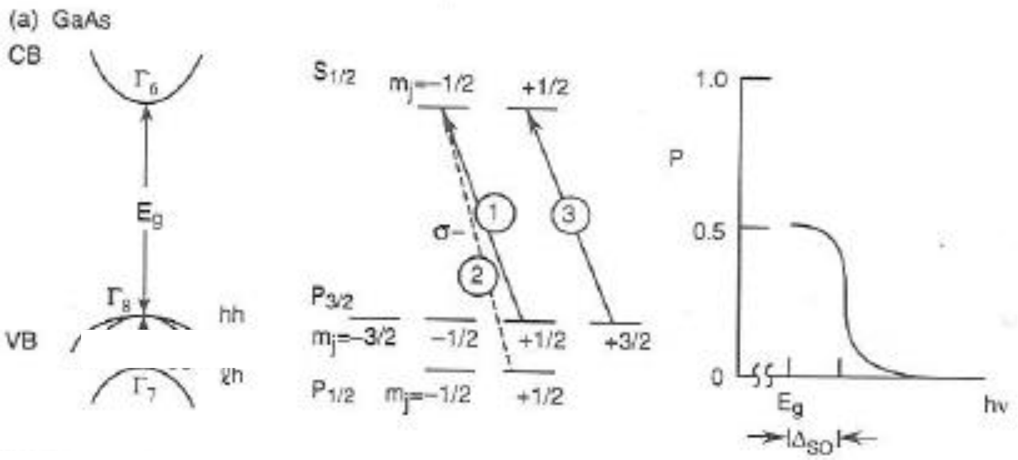
Daniel T. Pierce* and Felix Meier

Laboratorium für Festkörperphysik, Eidgenössische Technische Hochschule, CH 8049, Zürich, Switzerland



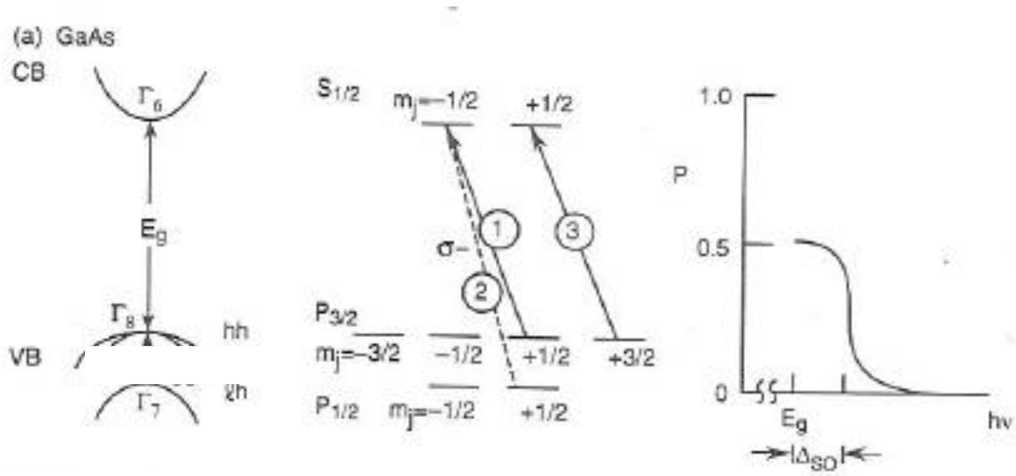


Towards P > 50%



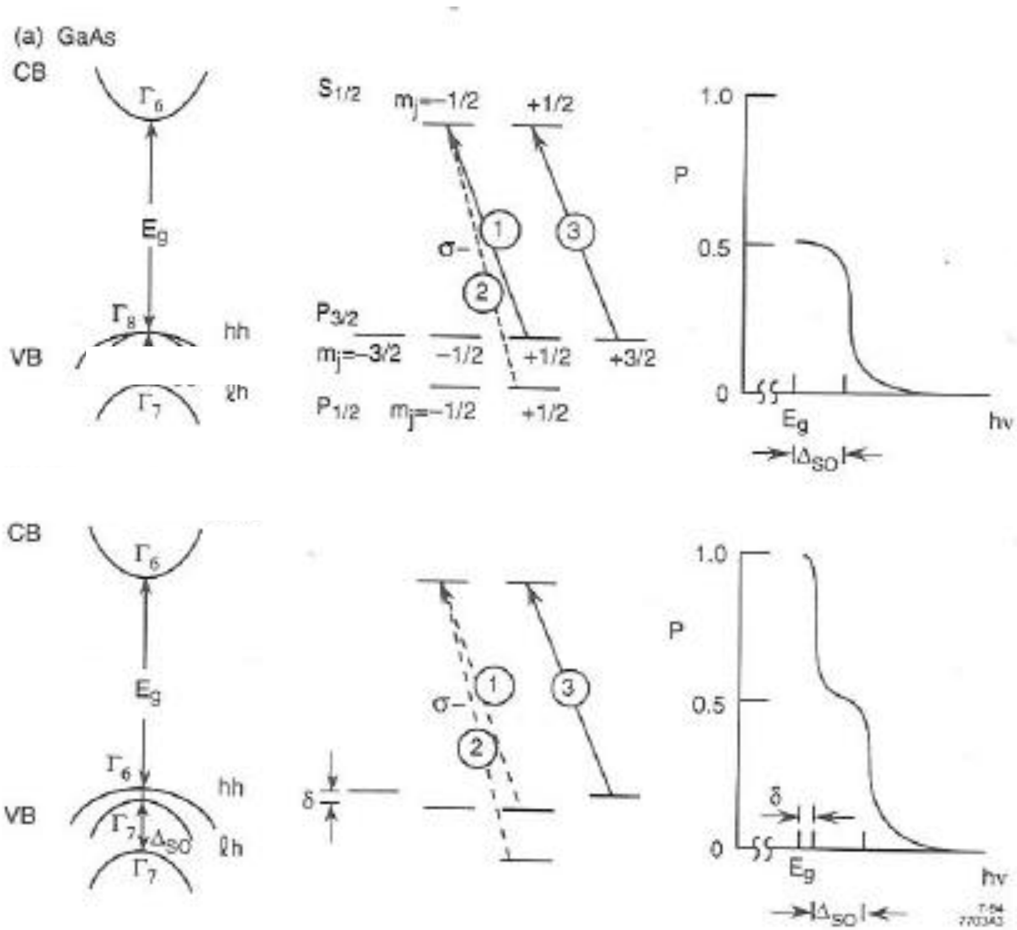
(a) GaAs
CB
VB
Eg
hh
S1/2
mj=−1/2
+1/2
σ−
P3/2
mj=−3/2
−1/2
+1/2
+3/2
P1/2
mj=−1/2
+1/2
1.0
0.5
0
P
Eg
hν
ΔSO

Towards P > 50%



P> 50% → remove HH-LH degeneracy
no-cubic symmetry

Towards P > 50%



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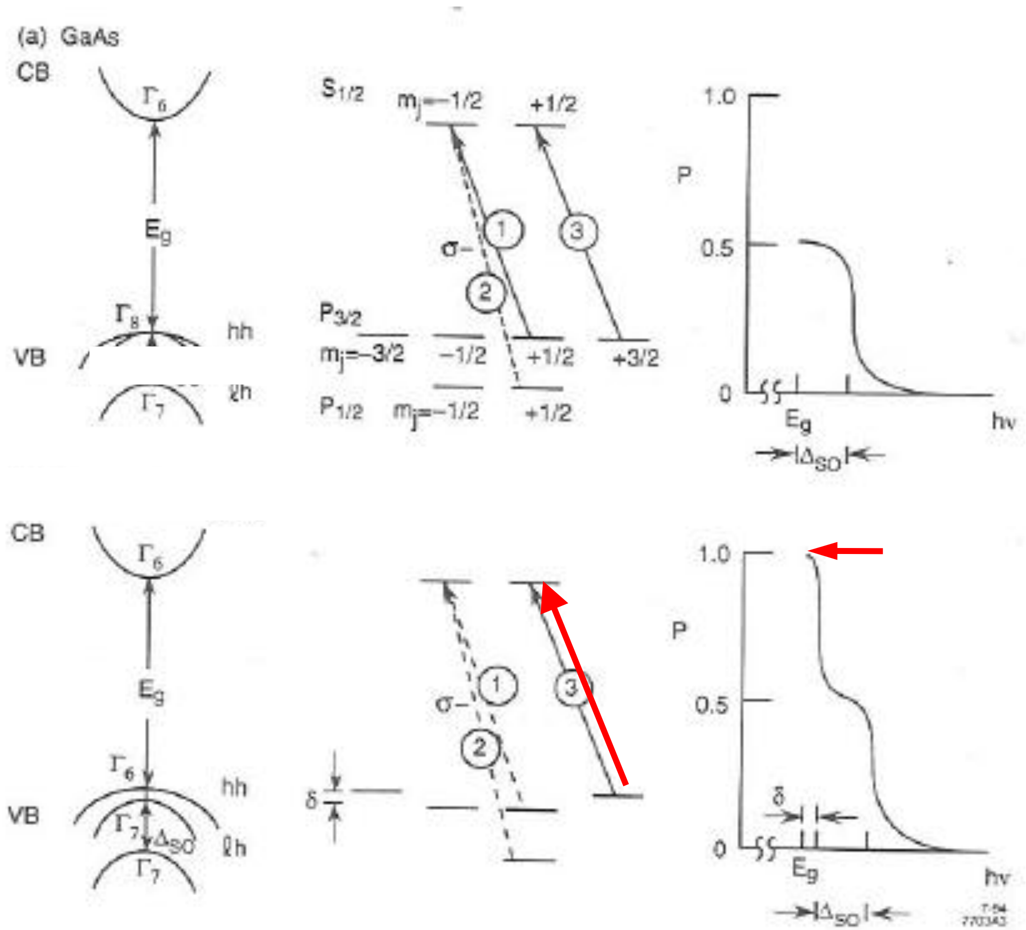

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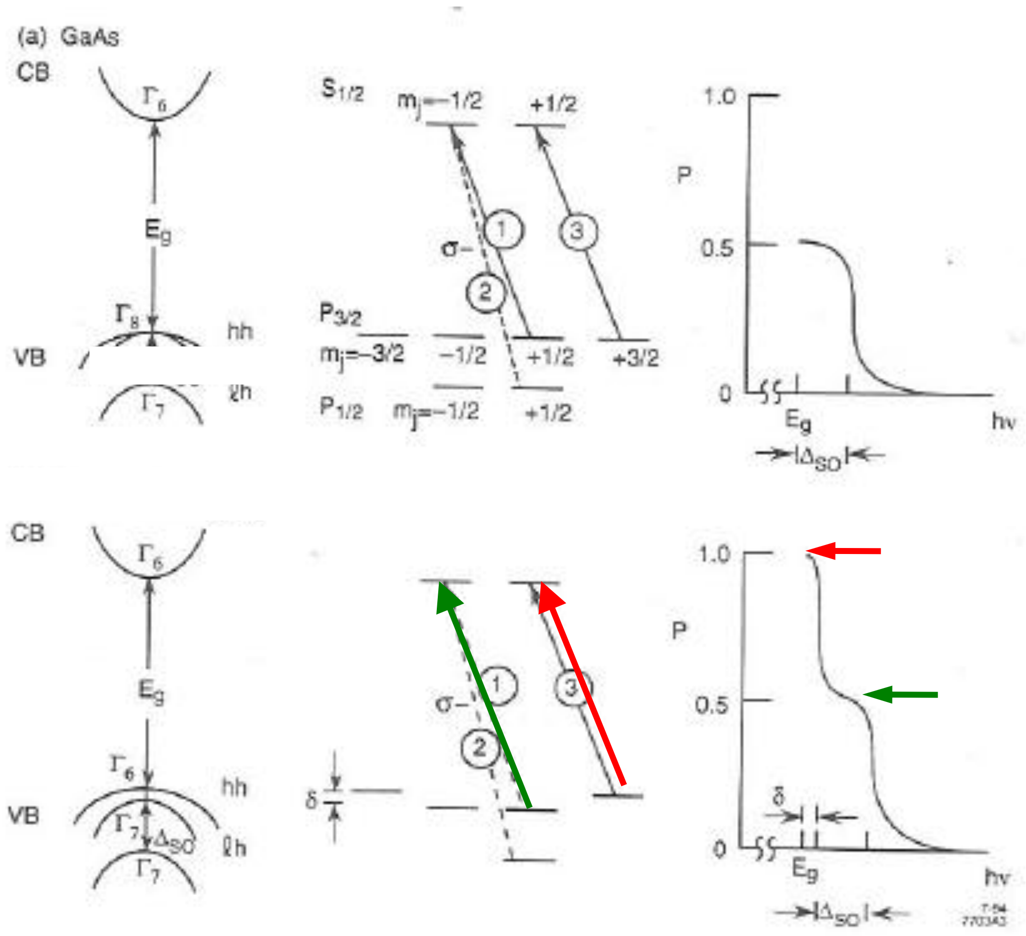

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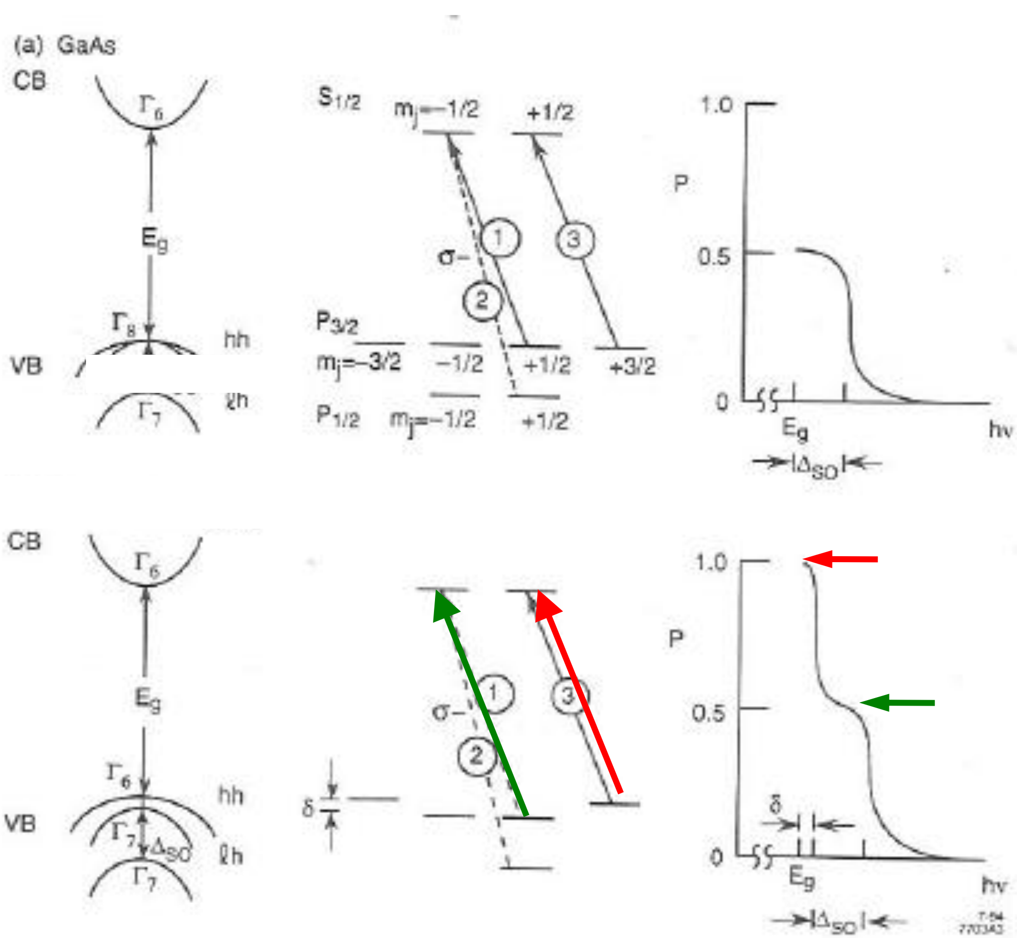


P> 50% → remove HH-LH degeneracy
no-cubic symmetry

Proposal ('80s):

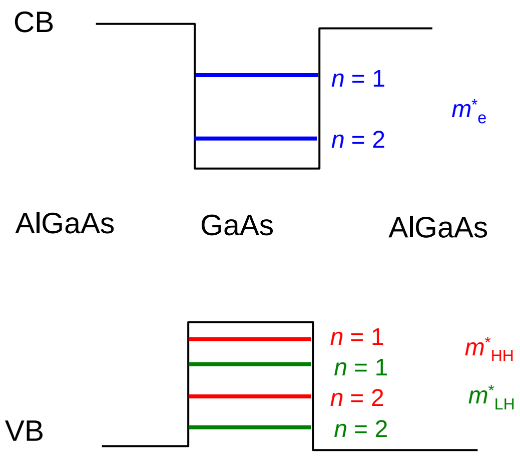
GaAs + mechanical uniaxial stress

Hexagonal semiconductros (CdSe)

Chalcopyretes

GaAs/AlGaAs quantum wells (QW) and superlattices (SL)

AlGaAs/GaAs QW and SL



VOLUME 33, NUMBER 14 PHYSICAL REVIEW LETTERS 30 SEPTEMBER 1974

Quantum States of Confined Carriers in Very Thin $Al_xGa_{1-x}As$-GaAs-$Al_xGa_{1-x}As$ Heterostructures

R. Dingle, W. Wiegmann, and C. H. Henry
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 24 June 1974)

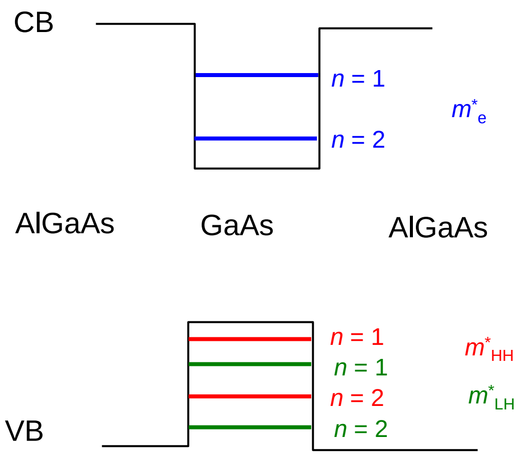
the energies of the bound states are

$$E = E_n + (\hbar^2/2m)(k_x^2 + k_y^2),$$

where

$$E_n = (\hbar^2\pi^2/2m)(n/L_z)^2, \quad n = 1, 2, 3.$$

AlGaAs/GaAs QW and SL



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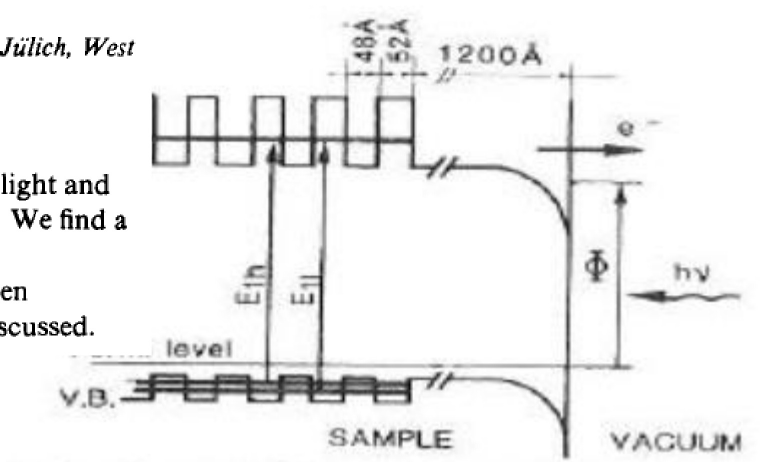
615 Appl. Phys. Lett. **39**(8), 15 October 1981

GaAs-Al_xGa_{1-x}As superlattices as sources of polarized photoelectons

S. F. Alvarado, F. Ciccacci, and M. Campagna
Institut für Festkörperforschung, Kernforschungsanlage Jülich GmbH, Postfach 1913, D-5170 Jülich, West Germany

(Received 8 June 1981; accepted for publication 30 July 1981)

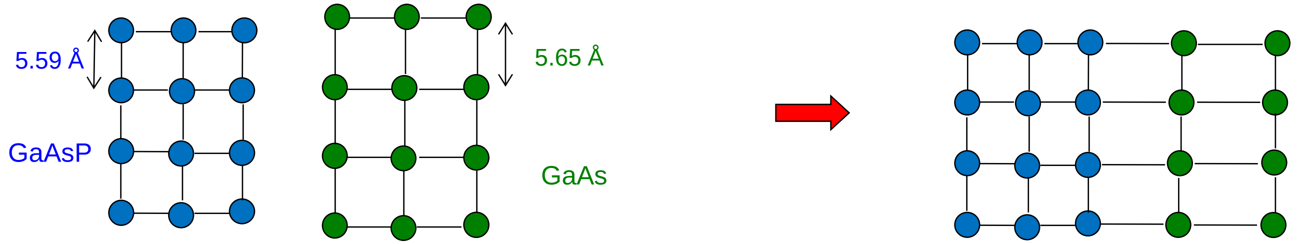
We have measured the spin polarization of electrons optically pumped by polarized light and photoemitted from GaAs-Al_xGa_{1-x}As superlattices with negative electron affinity. We find a maximum polarization of 49%, in contrast to the expectations related to polarized photoluminescence studies. Reasons for these findings based on the difference between photoemission from negative electron affinity sources and photoluminescence are discussed.



P_{max} = 49% (@ RT)

Epitaxial strained thin films

Epitaxial strained thin films



Physics Letters A 158 (1991) 345–349
North-Holland

PHYSICS LETTERS A

Large enhancement of spin polarization observed by photoelectrons from a strained GaAs layer

T. Nakanishi [a], H. Aoyagi [a], H. Horinaka [b], Y. Kamiya [c], T. Kato [d], S. Nakamura [a,1], T. Saka [d] and M. Tsubata [a]

[a] *Department of Physics, Nagoya University, Nagoya 464, Japan*
[b] *College of Engineering, Osaka Prefecture University, Sakai 591, Japan*
[c] *Toyota Technical Institute, Nagoya 468, Japan*
[d] *New Materials Research Laboratory, Daido Steel Co. Ltd, Nagoya 457, Japan*

Received 17 May 1991; revised manuscript received 4 July 1991; accepted for publication 14 July 1991
Communicated by J.I. Budnick

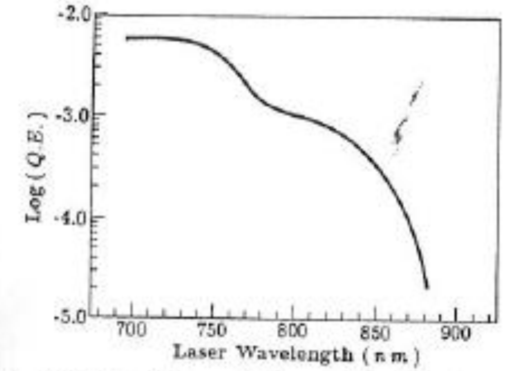
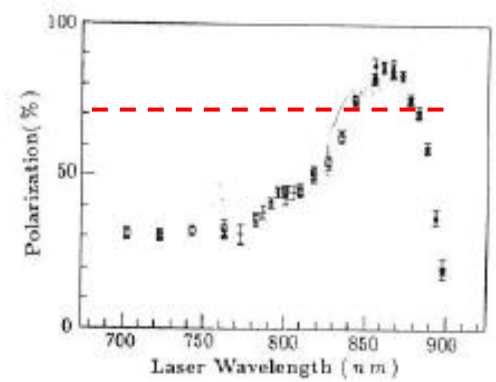


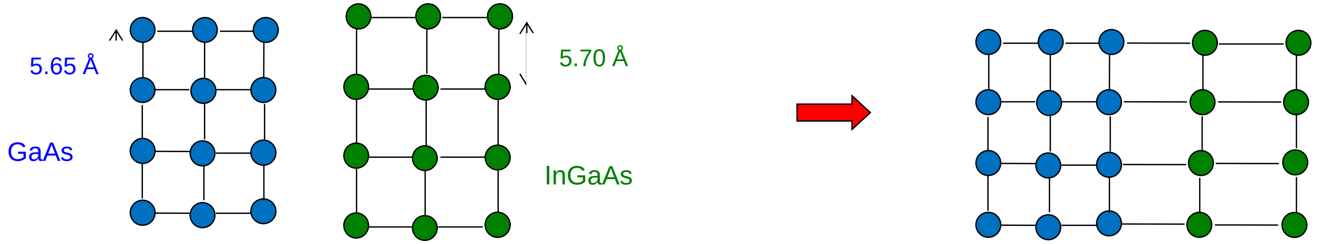
Fig. 1. Quantum efficiency of photoemission from STP2 as function of the wavelength of the laser photon.

80 nm GaAs film grown on GaAsP(001)

We have observed a large enhancement of the spin polarization of photoelectrons emitted from a 0.08 μm thick strained GaAs(001) layer grown on a GaP_xAs_{1-x} substrate by the MOCVD method with $x=0.17$. For this fraction of phosphorus, the lattice-mismatch was estimated to be ~0.6% and the energy splitting between heavy-hole and light-hole bands at the valence band maximum to be ~40 meV. The maximum polarization of ~86% was observed with a quantum efficiency of $\sim 2\times10^{-4}$, under the conditions that the cathode was at room temperature and the excitation photon wavelength was $\lambda \approx 860$ nm.



Epitaxial strained thin films



VOLUME 66, NUMBER 18 PHYSICAL REVIEW LETTERS 6 MAY 1991

Observation of Strain-Enhanced Electron-Spin Polarization in Photoemission from InGaAs

T. Maruyama and E. L. Garwin

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

R. Prepost and G. H. Zapalac

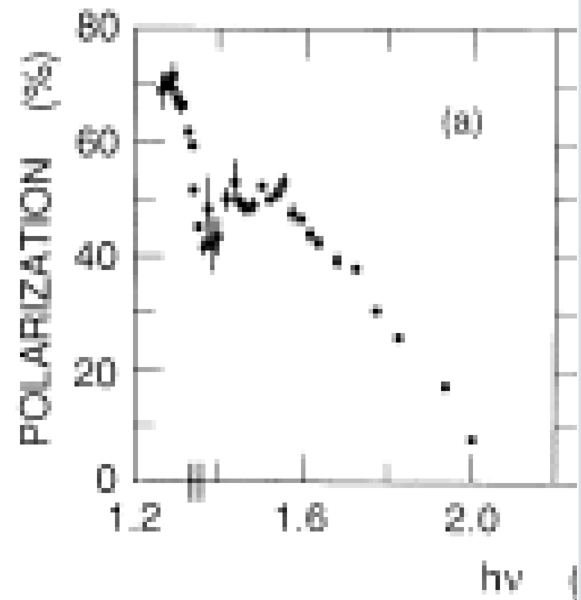
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706

J. S. Smith and J. D. Walker

Department of Electrical Engineering and Computer Sciences and The Electronics Research Laboratory, University of California, Berkeley, California 94720

(Received 26 February 1991)

Electron-spin polarization in excess of 70% has been observed in photoemission from a 0.1-μm-thick epitaxial layer of $In_xGa_{1-x}As$ with $x \approx 0.13$ grown on a GaAs substrate. Under these conditions, the epitaxial layer is expected to be highly strained by the 0.9% lattice mismatch. The electron polarization and the quantum efficiency have been measured as a function of the excitation photon energy from 1.25 to 2.0 eV. A significant enhancement of the electron polarization occurs in the vicinity of 1.33 eV where the expected strain-induced level splitting permits optical excitation of a single-band transition.



100 nm InGaAs film grown on GaAs(001)

Optical pumping: applications

GaAs spin polarized electron source

D.T. Pierce, R.J. Celotta, G.-C. Wang, W.N. Unertl, C.E. Kuyatt, and S.R. Mielczarek

Rev. Sci. Instrum. 51(4), 478, (1980)

- High intensity
- High polarization (40%)
- Fast and easy electron polartization reversal

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High Energy and Nuclear Physics

Spin dependent properties in accelerators

Elementary particle physics (nuclei, quarks, gauge bosons)

C.K. Sinclair et al., High energy physics with polarized beams and polarized targets, AIP Conf. Proc. **35** (AIP, New York 1976)

J. E. Clendenin et al., Nucl. Instrum. Meth. A **536**, 308-311 (2005)

Optical pumping: applications

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- High polarization (40%)
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Spectroscopy of (magnetic) solids

U. Kolac, M. Donath, K. Ertl, H. Liebl, V. Dose, Rev. Sci. Instrum. **59**, 1933 (1988) (bulk)

F. Ciccacci, E. Vescovo, G.Chiaia, S. De Rossi, M. Tosca, Rev. Sci. Instrum. **63**, 3333 (1992) (bulk)

F. Ciccacci, S. De Rossi, E. Pelucchi, A.Tagliaferri, Rev. Sci. Instrum **68**, 1841 (1997) (nanostructures)

SPLEED- SPELS

R.J. Celotta, D.T. Pierce, G.-C. Wang, S.D. Bader, G.P. Felcher, Phy. Rev. Lett. **43**, 728 (1979)

S.F. Alvarado, R. Feder, H. Hopster, F. Ciccacci, H. Pleyer, Z. Phys. B **49**, 129 (1982)

review: R. Feder (ed) Polarized Electrons in Surface Physics (World Scientific, Singapore 1985)

SPIPE

J. Unguris, A. Seiler, R.J. Celotta, D.T. Pierce, P.D.Johnson, N. Smith,ys. Rev. Lett. **49**, 1047 (1982)

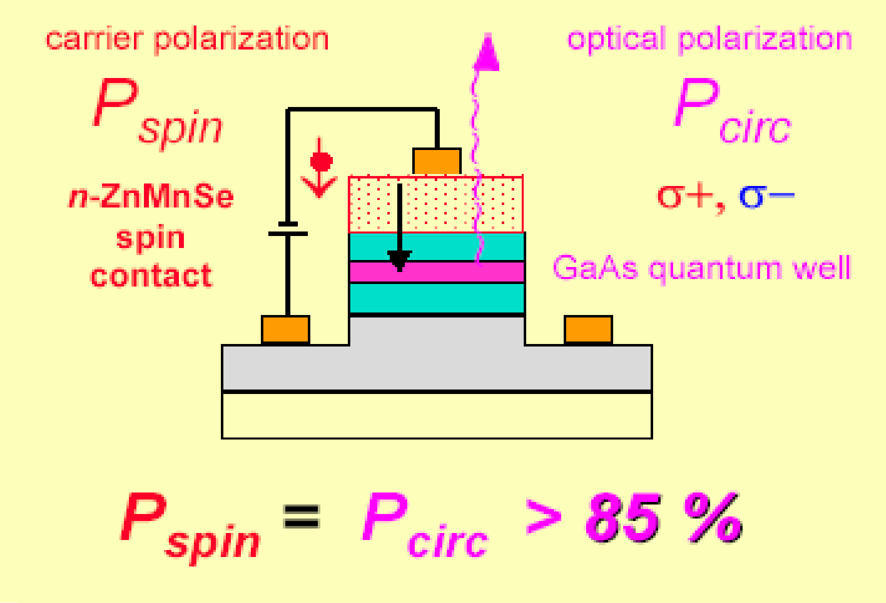
F. Ciccacci, G. Chiaia, S. De Rossi, Solid State Commun. **88**, 827 (1993)

review: M. Donath, Surface Sci. Rep. **20**, 251 (1994)

F. Ciccacci, Phys. Scrip. T **66**, 190 (1996)

Optical pumping: applications

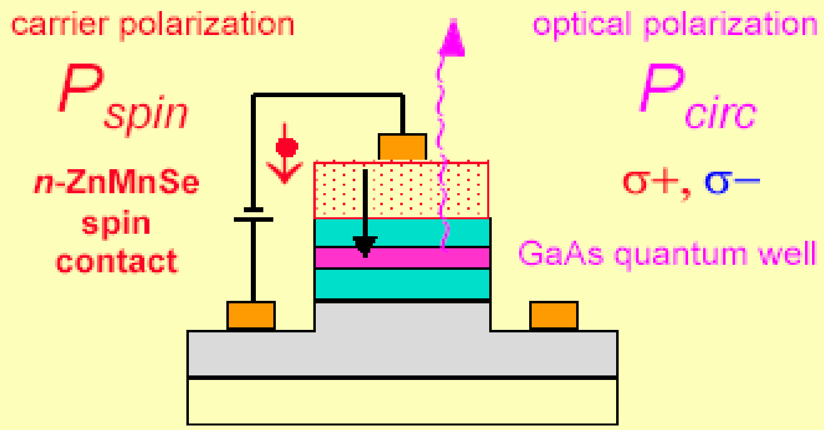
Spin-LED



B.T. Jonker & C.
Phy. Rev. B 62, 8180 (2000);
Appl. Phys. Lett. 80, 1240 (2002)

Optical pumping: applications

Spin-LED



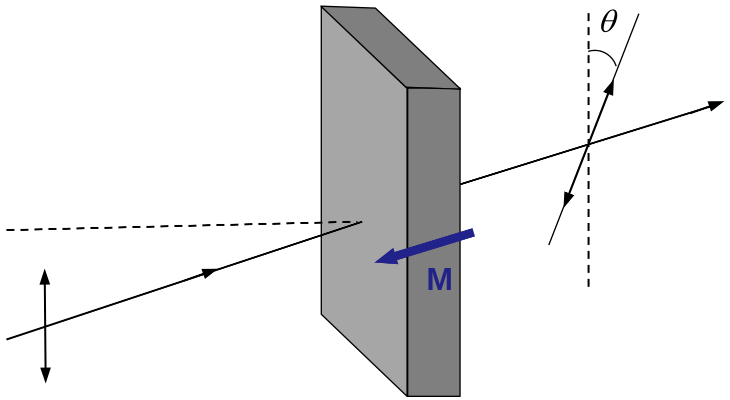
$$P_{spin} = P_{circ} > 85\ \%$$

B.T. Jonker & C.
Phy. Rev. B 62, 8180 (2000);
Appl. Phys. Lett. 80, 1240 (2002)

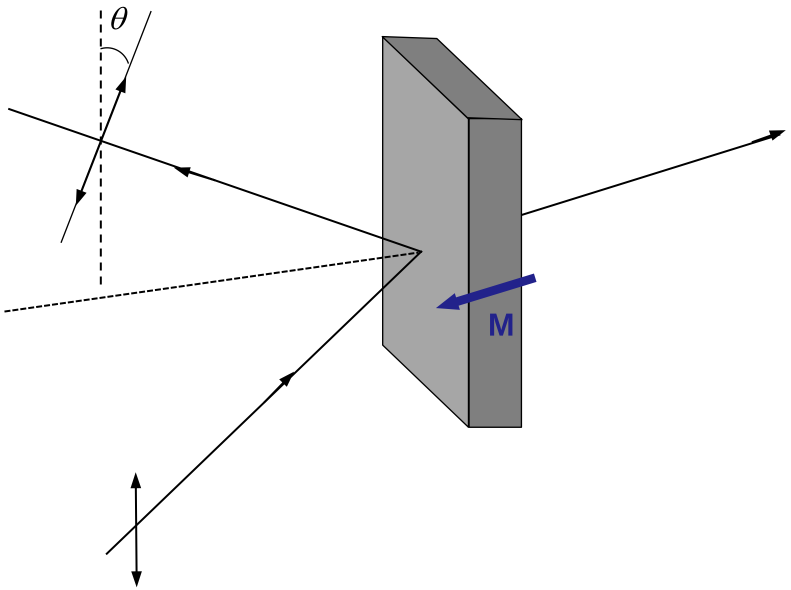
Spin-PD

C. Rinaldi et al., Adv. Mat. 24 3037 (2012)

Magneto-optics

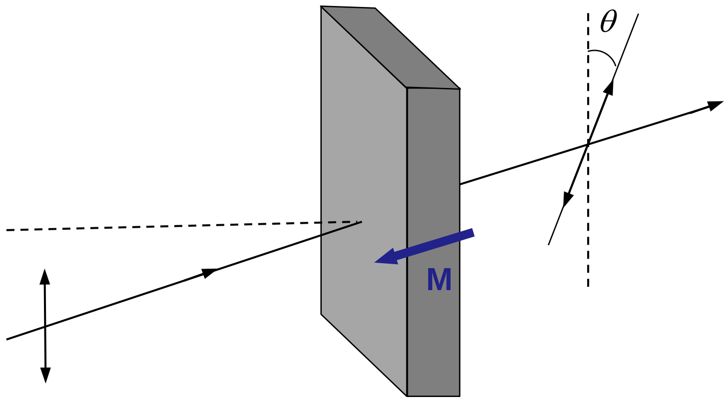


transmission (Faraday)

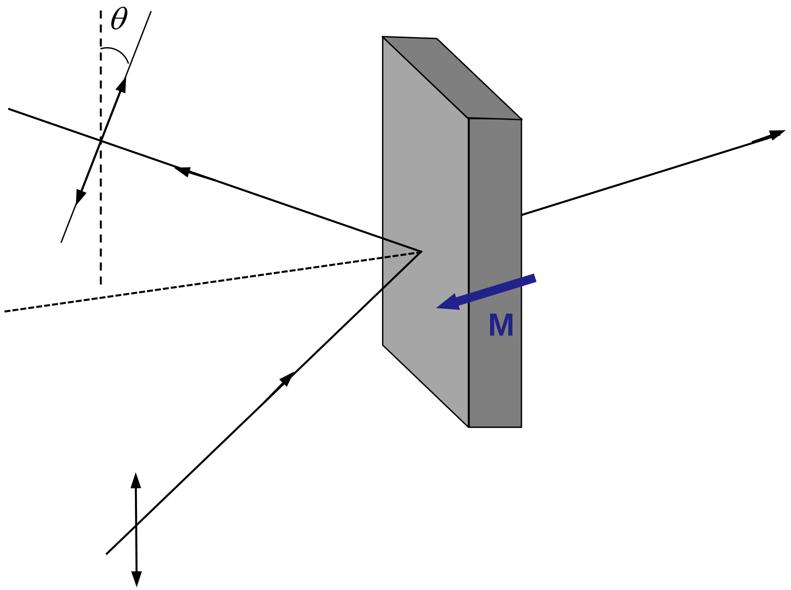


reflection (Kerr)

Magneto-optics

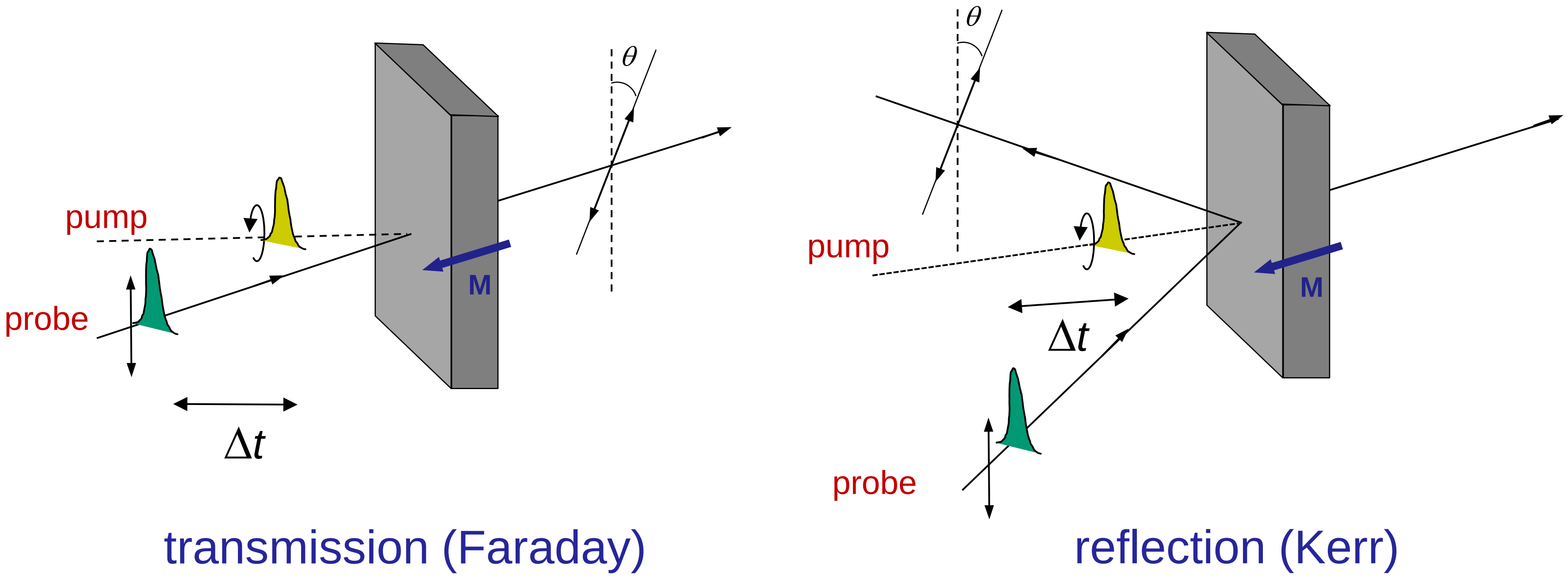


transmission (Faraday)



reflection (Kerr)

$$\mathbf{M} \rightarrow P = (n\uparrow - n\downarrow)/(n\uparrow + n\downarrow)$$



time resolved

Spin dynamics and transport

- Polarized luminescenze *versus* *T* , **B** , doping (*n, p*)

- Magneto-optic effects

- Time resolved (pump-probe)

Electron (hole) spin relaxation mechanisms

Electron (hole) transport

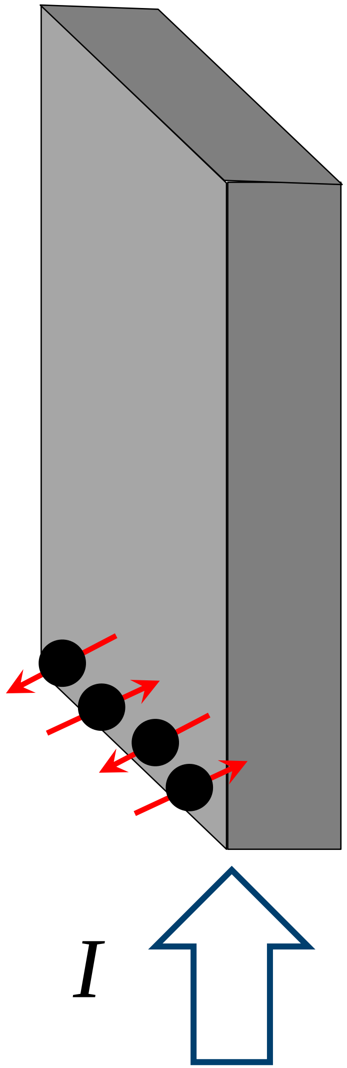
Electron (hole) scattering

Coherence

F. Meier, B.P. Zakharchenya, O*ptical orientation,* North Holland, Amsterdam, 1984

D.D.Awschalom et al., Phys. Today 52, 33 (1999); Science 294, 1488 (2001)

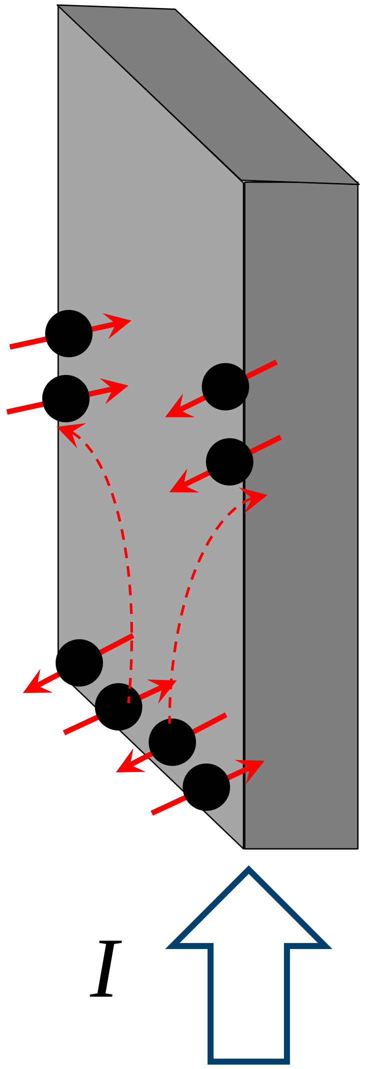
Spin Hall Effect (SHE)



Spin Hall Effect (SHE)

Spin dependent (Mott) scattering

(opposite) spin accumulation at sample edges



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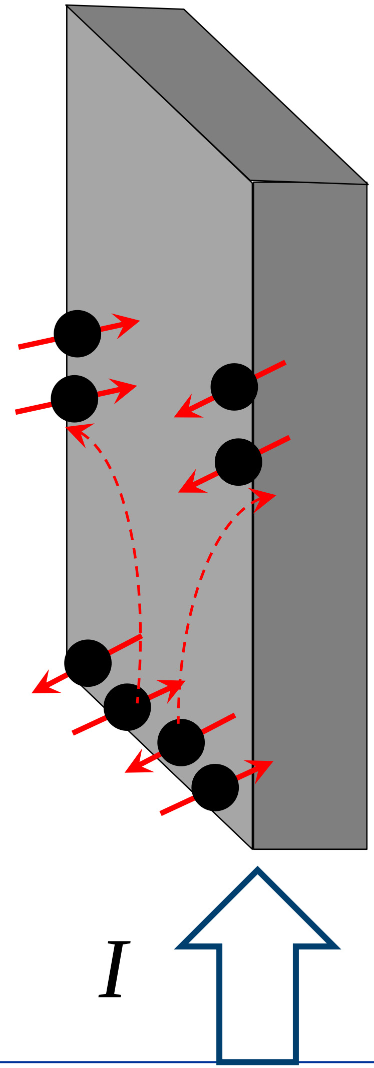


detectable via Kerr effect

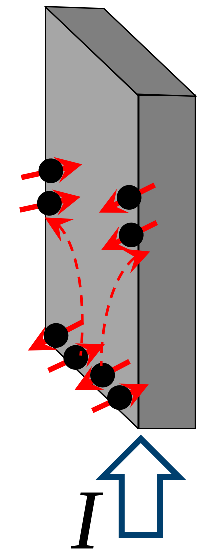
Spin Hall Effect (SHE)

1910 10 DECEMBER 2004 VOL 306 SCIENCE

Observation of the Spin Hall Effect in Semiconductors

Y. K. Kato, R. C. Myers, A. C. Gossard, D. D. Awschalom*

Electrically induced electron-spin polarization near the edges of a semiconductor channel was detected and imaged with the use of Kerr rotation microscopy. The polarization is out-of-plane and has opposite sign for the two edges, consistent with the predictions of the spin Hall effect. Measurements of unstrained gallium arsenide and strained indium gallium arsenide samples reveal that strain modifies spin accumulation at zero magnetic field. A weak dependence on crystal orientation for the strained samples suggests that the mechanism is the extrinsic spin Hall effect.



GaAs

Spin Hall Effect (SHE)

1910 10 DECEMBER 2004 VOL 306 SCIENCE

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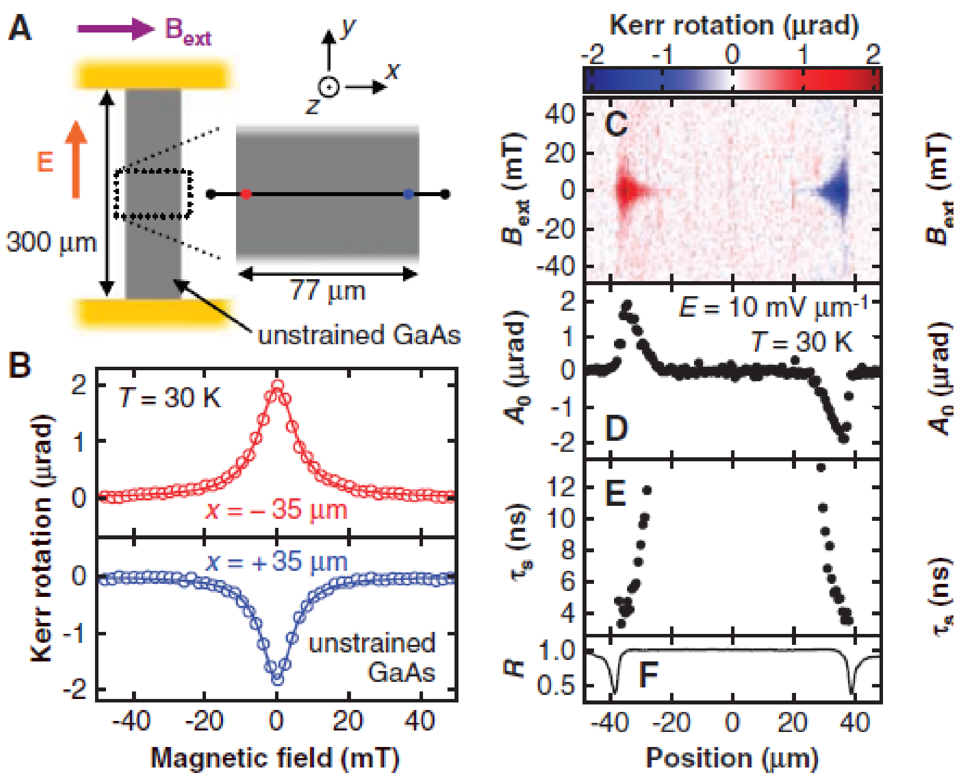


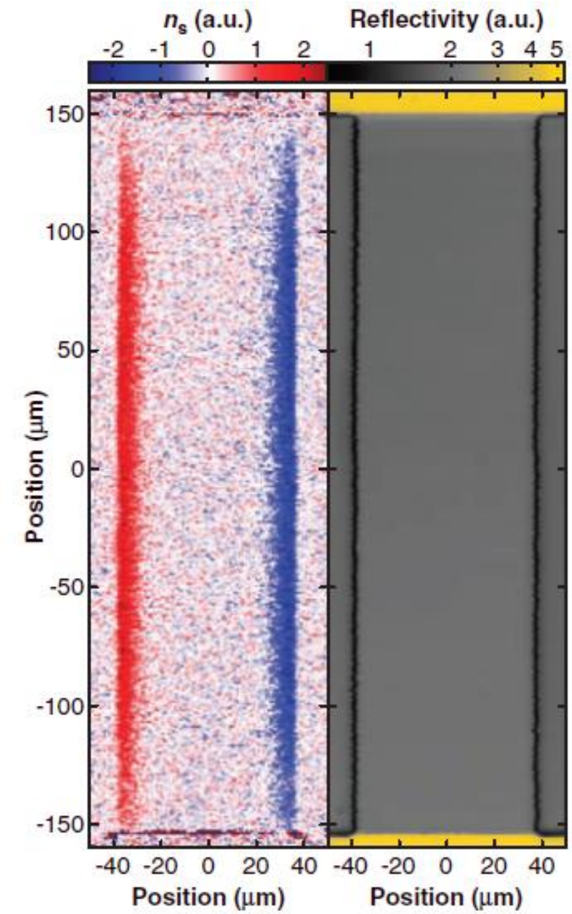
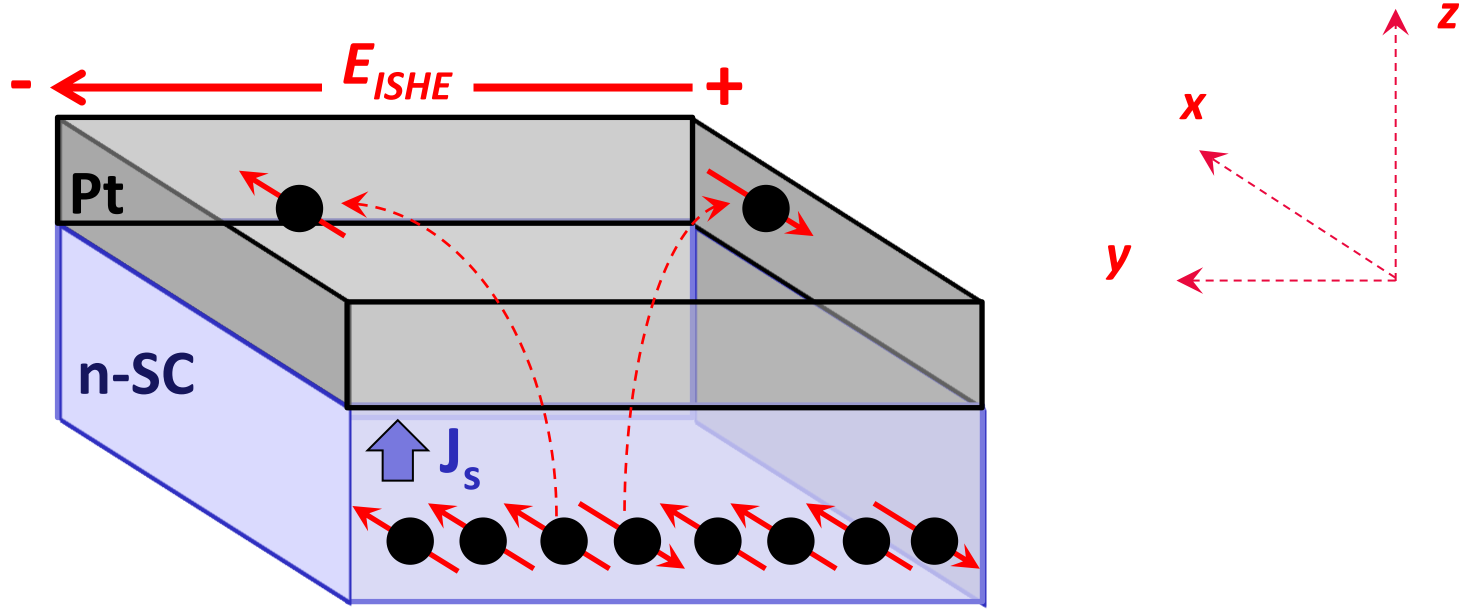
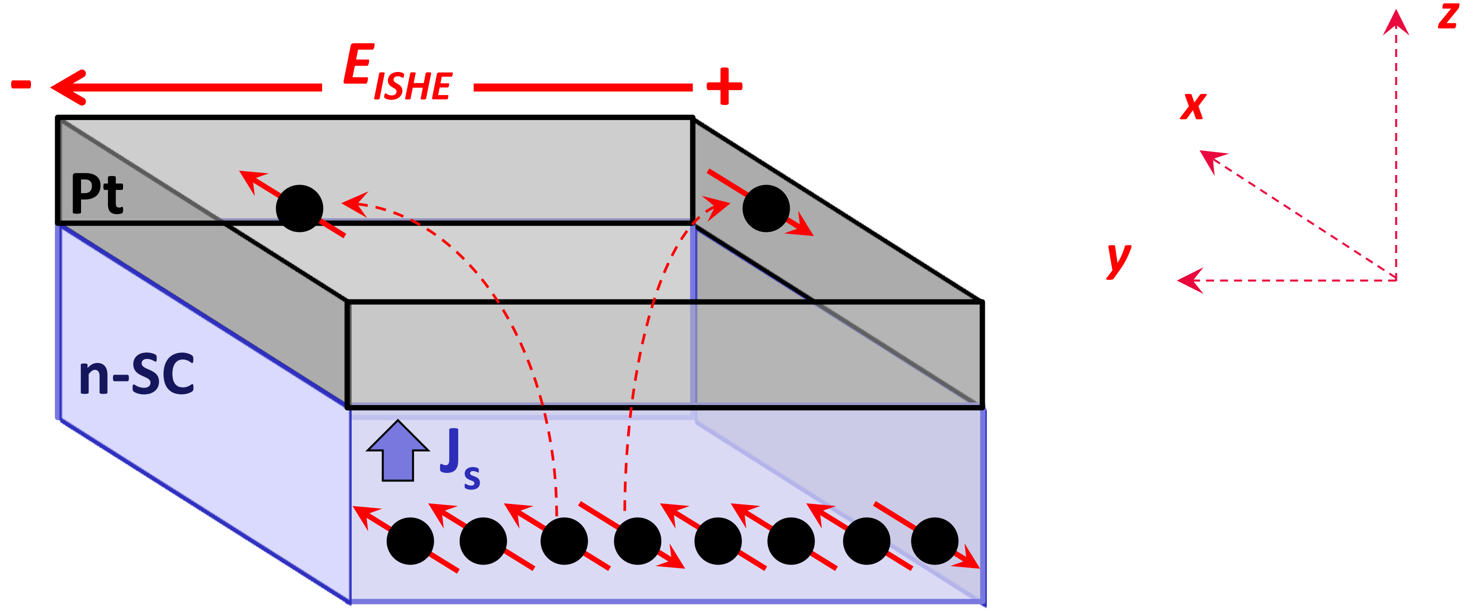


Fig. 2. (A and B) Two-dimensional images of spin density n_s and reflectivity R, respectively, for the unstrained GaAs sample measured at T = 30 K and E = 10 mV µm^{-1}.

Inverse Spin Hall Effect (ISHE)

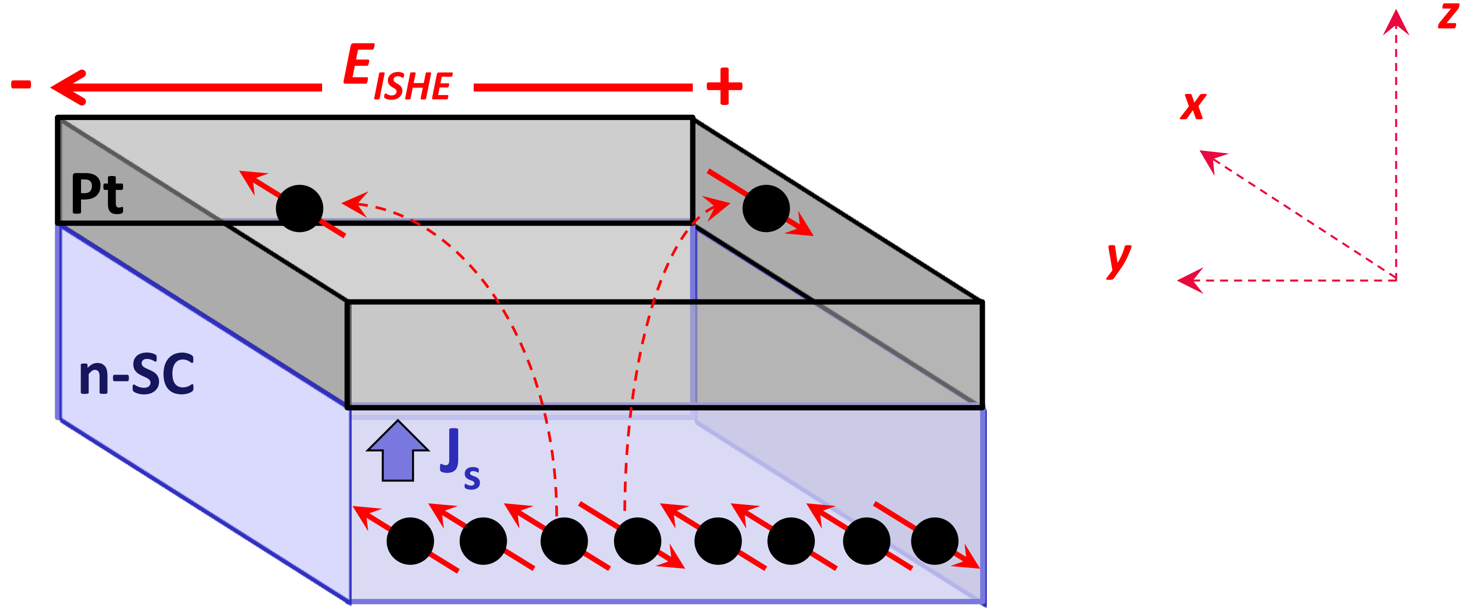


Inverse Spin Hall Effect (ISHE)



$$E_{ISHE} = \frac{\gamma}{\sigma_c} \; J_s \; x \; P$$

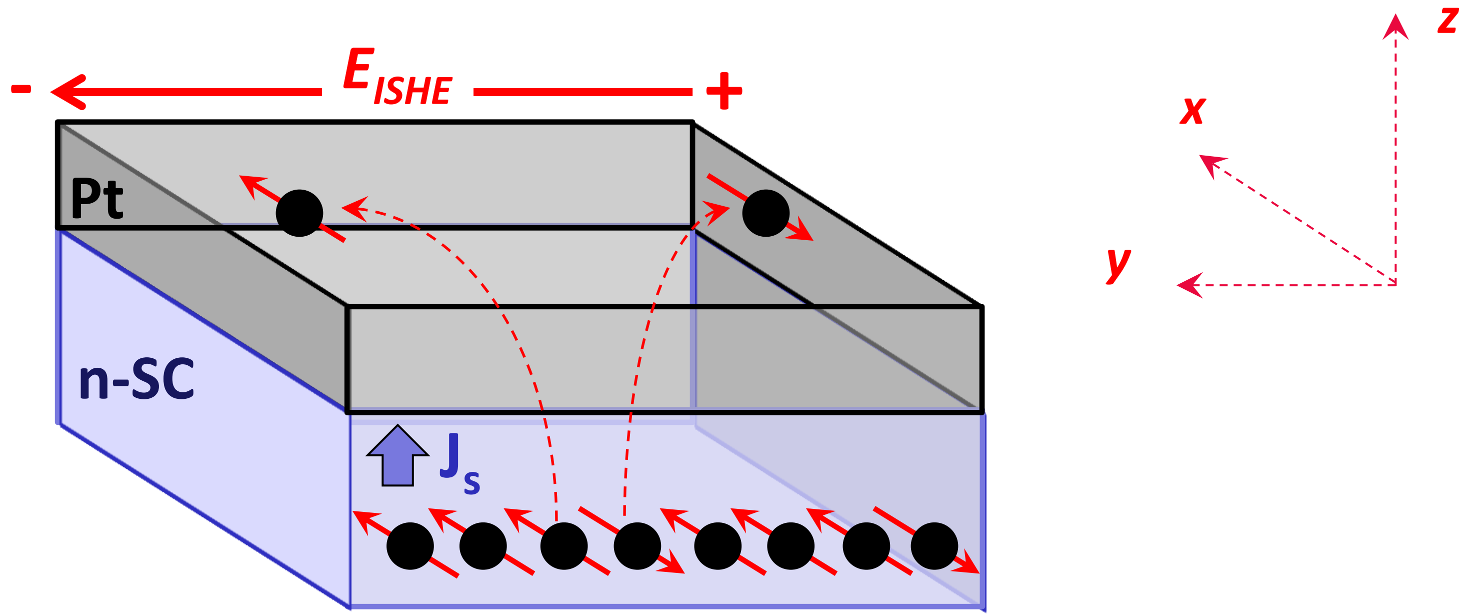
Inverse Spin Hall Effect (ISHE)



$$E_{ISHE} = \frac{\gamma}{\sigma_c} J_s \times P$$

z-axis

Inverse Spin Hall Effect (ISHE)

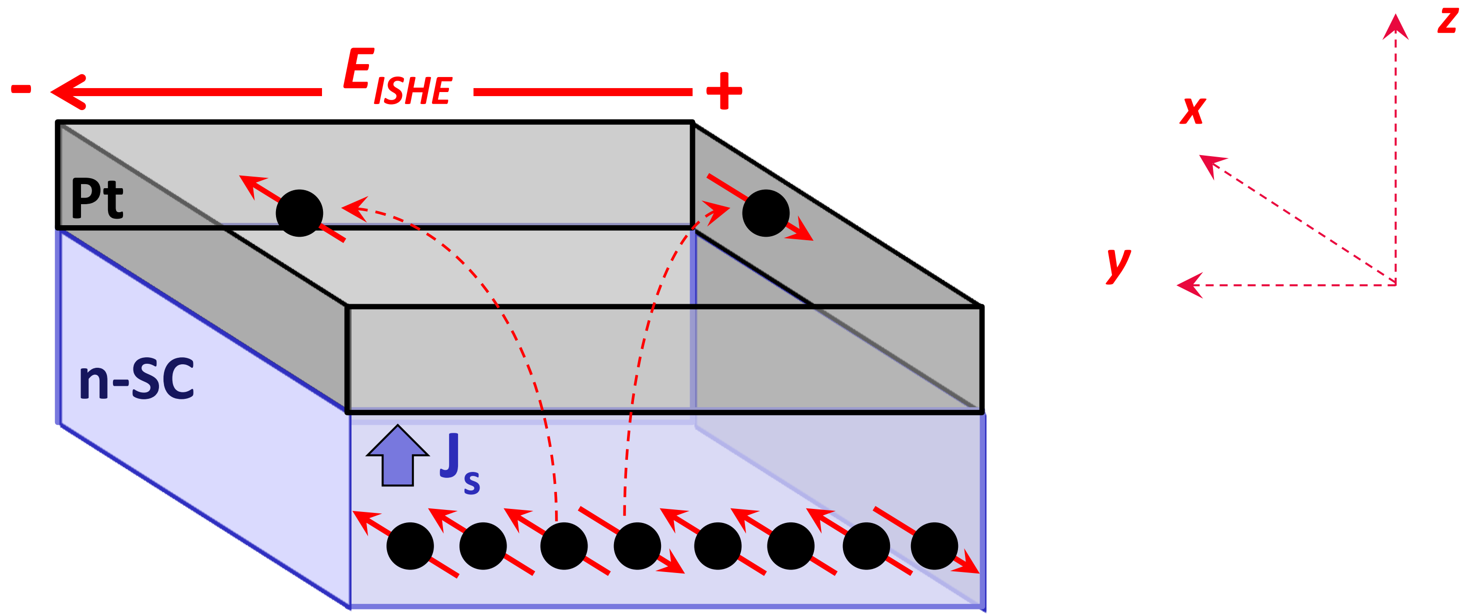


$$E_{ISHE} = \frac{\gamma}{\sigma_c} J_s \times P$$

E_{ISHE} → *y*-axis

J_s → *z*-axis

Inverse Spin Hall Effect (ISHE)



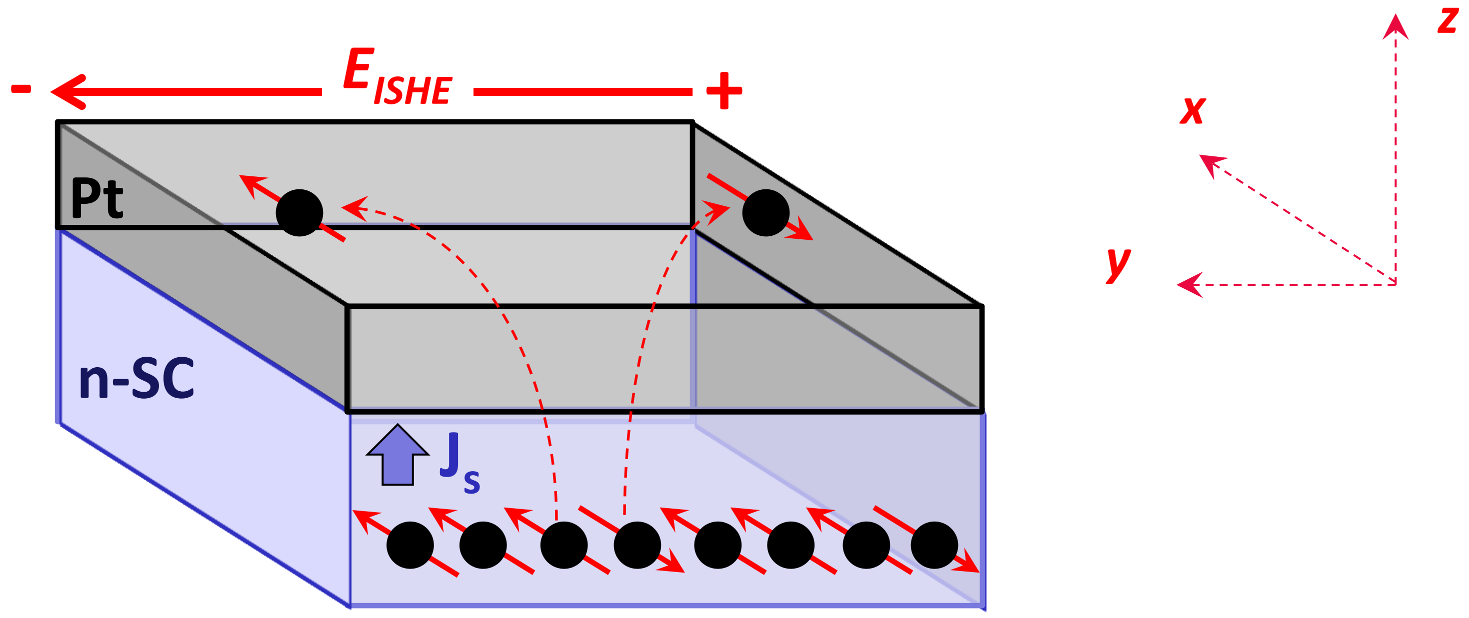
$$E_{ISHE} = \frac{\gamma}{\sigma_c} J_s \times P$$

E_{ISHE} → *y*-axis

J_s → *z*-axis

P → *x*-axis

Inverse Spin Hall Effect (ISHE)



$$E_{ISHE} = \frac{\gamma}{\sigma_c} J_s \times P$$

E_{ISHE} → y-axis; J_s → z-axis; P → x-axis

E_{ISHE} is proportional to P_x ⇒ maximization of spin polarization P_x

Optical ISHE

APPLIED PHYSICS LETTERS **96**, 082502 (2010)

Photoinduced inverse spin-Hall effect: Conversion of light-polarization information into electric voltage

K. Ando,[1,2,a)] M. Morikawa,[2] T. Trypiniotis,[3] Y. Fujikawa,[1] C. H. W. Barnes,[3] and E. Saitoh[1,2,4]

[1]*Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan*
[2]*Department of Applied Physics and Physico-Informatics, Keio University, Yokohama 223-8522, Japan*
[3]*Cavendish Laboratory, University of Cambridge, J. J. Thomson Avenue, Cambridge CB3 0HE, United Kingdom*
[4]*PRESTO, Japan Science and Technology Agency, Sanbancho, Tokyo 102-0075, Japan*

(Received 26 November 2009; accepted 30 January 2010; published online 23 February 2010)

The photoinduced inverse spin-Hall effect was observed in a Pt/GaAs hybrid structure. In the GaAs layer, circularly polarized light generates spin-polarized carriers, inducing a pure spin current into the Pt layer through the interface. This pure spin current is, by the inverse spin-Hall effect in the Pt layer, converted into electric voltage. By changing the direction and ellipticity of the circularly polarized light, the electromotive force varies systematically, consistent with the prediction of the photoinduced inverse spin-Hall effect. The observed phenomenon allows the direct conversion of circular-polarization information into electric voltage; this phenomenon can be used as a spin photodetector. © *2010 American Institute of Physics*. [doi:10.1063/1.3327809]

Pt/GaAs

APPLIED PHYSICS LETTERS 96, 082502 (2010)

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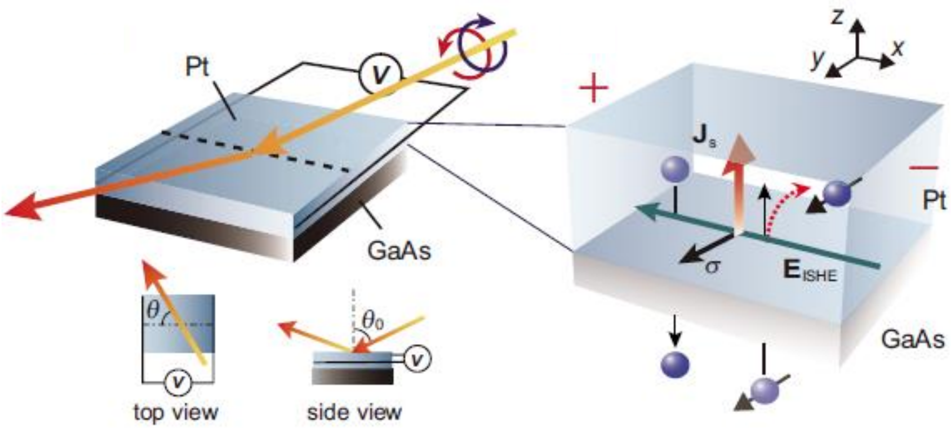
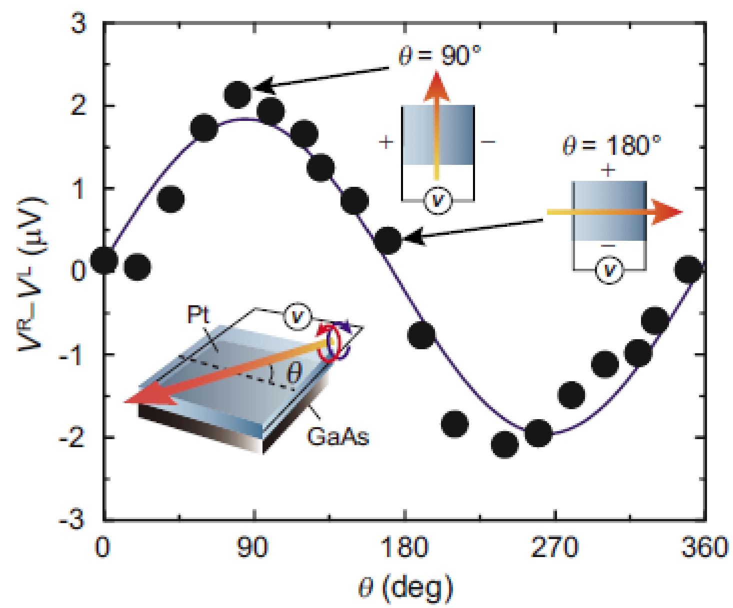
hν = 1.85 eV

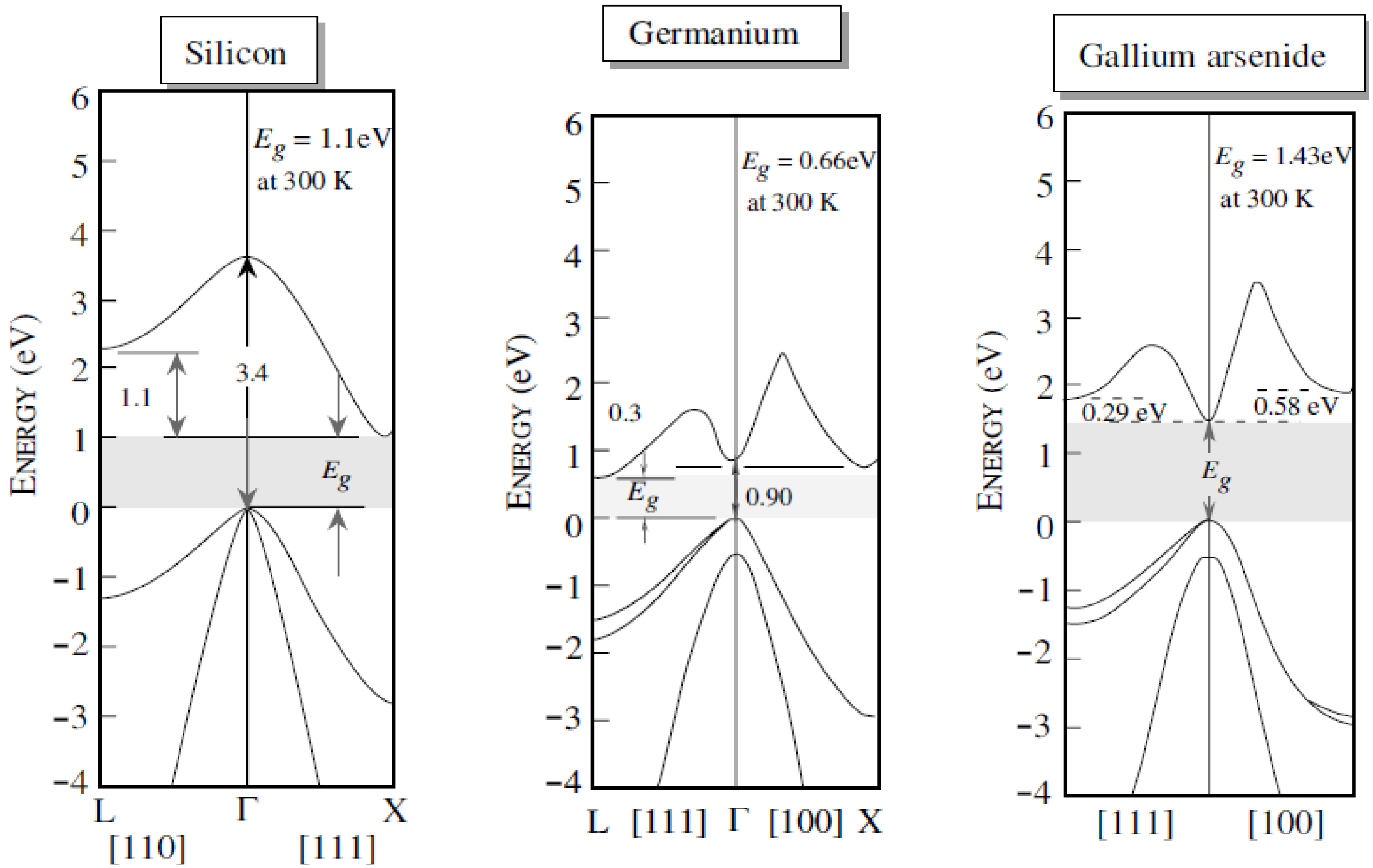
P = 10 mW





Pt/GaAs

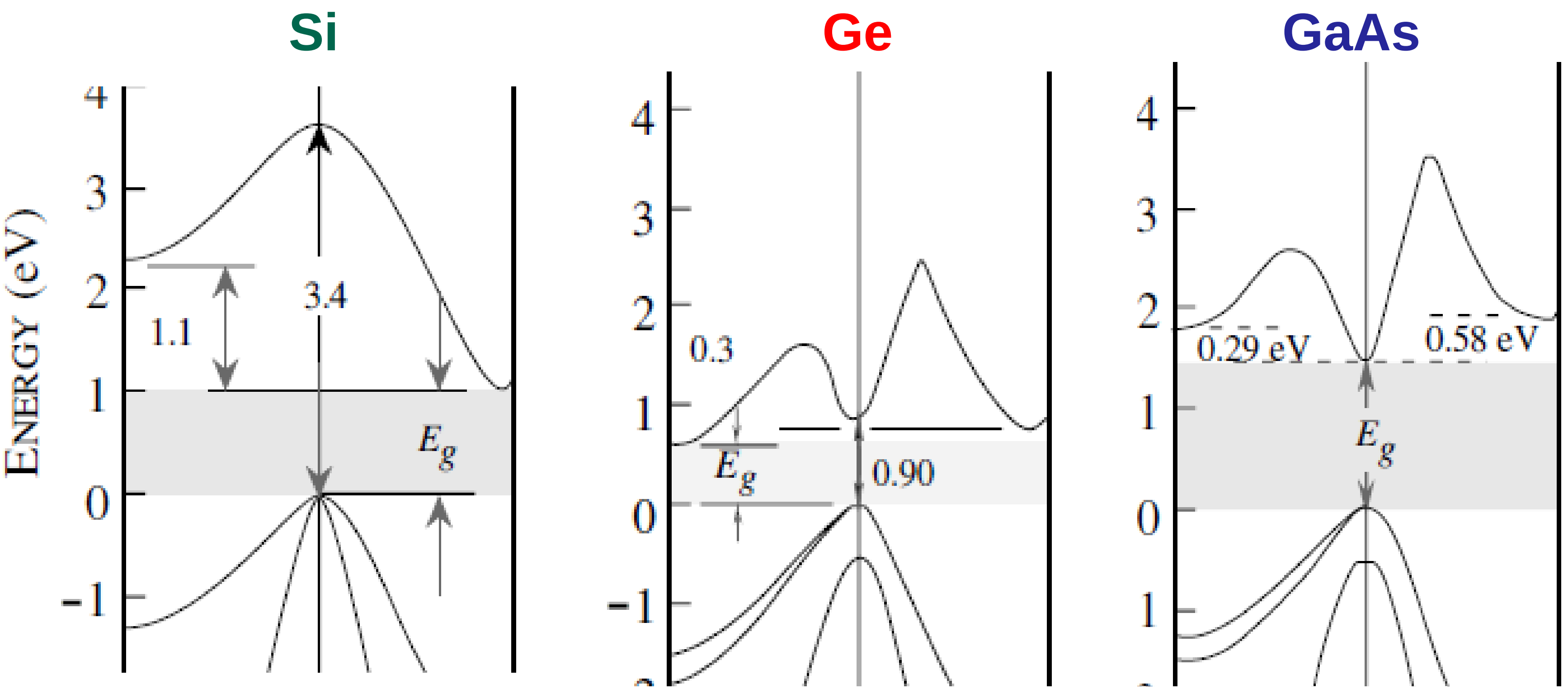
not only III-V…



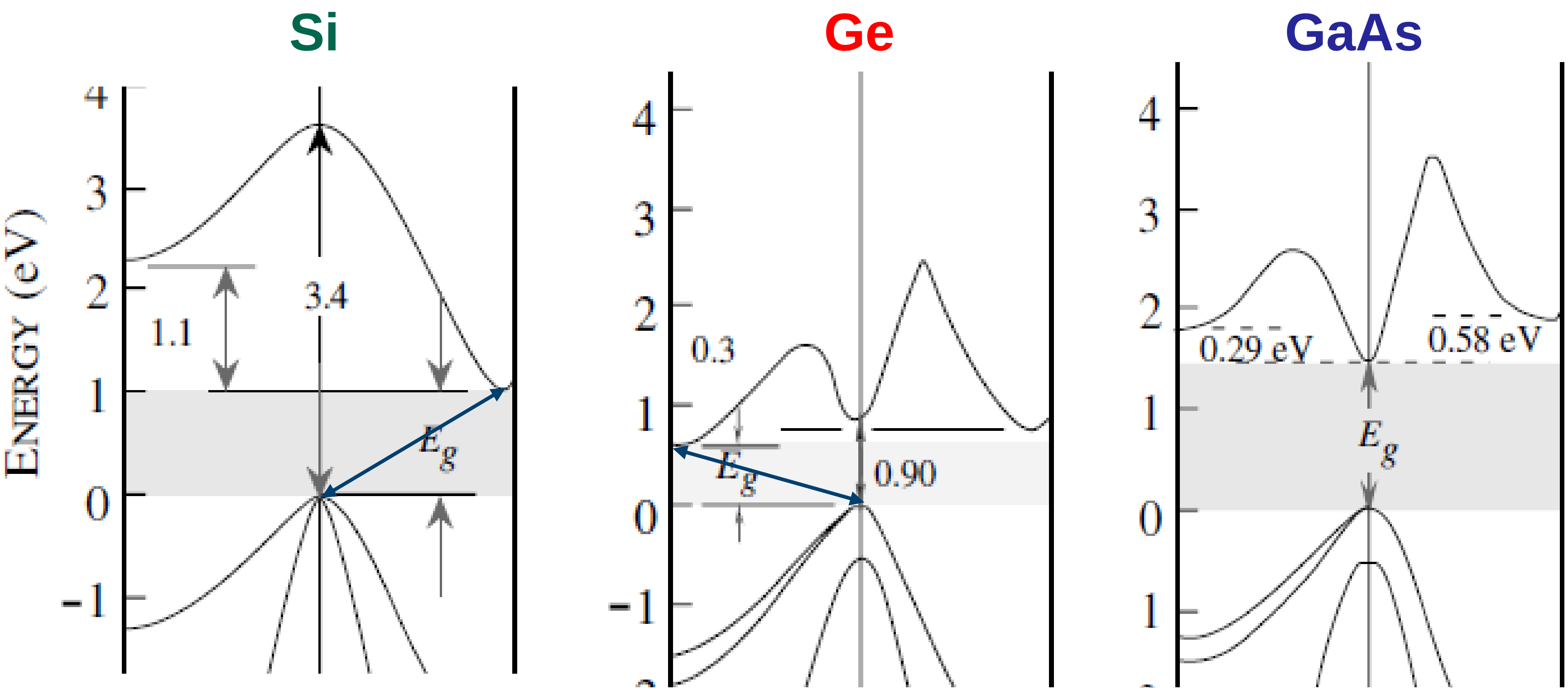
implement spin functionalities in group IV semiconductors

(optimally integrated in the well established Si-based electronics platform)

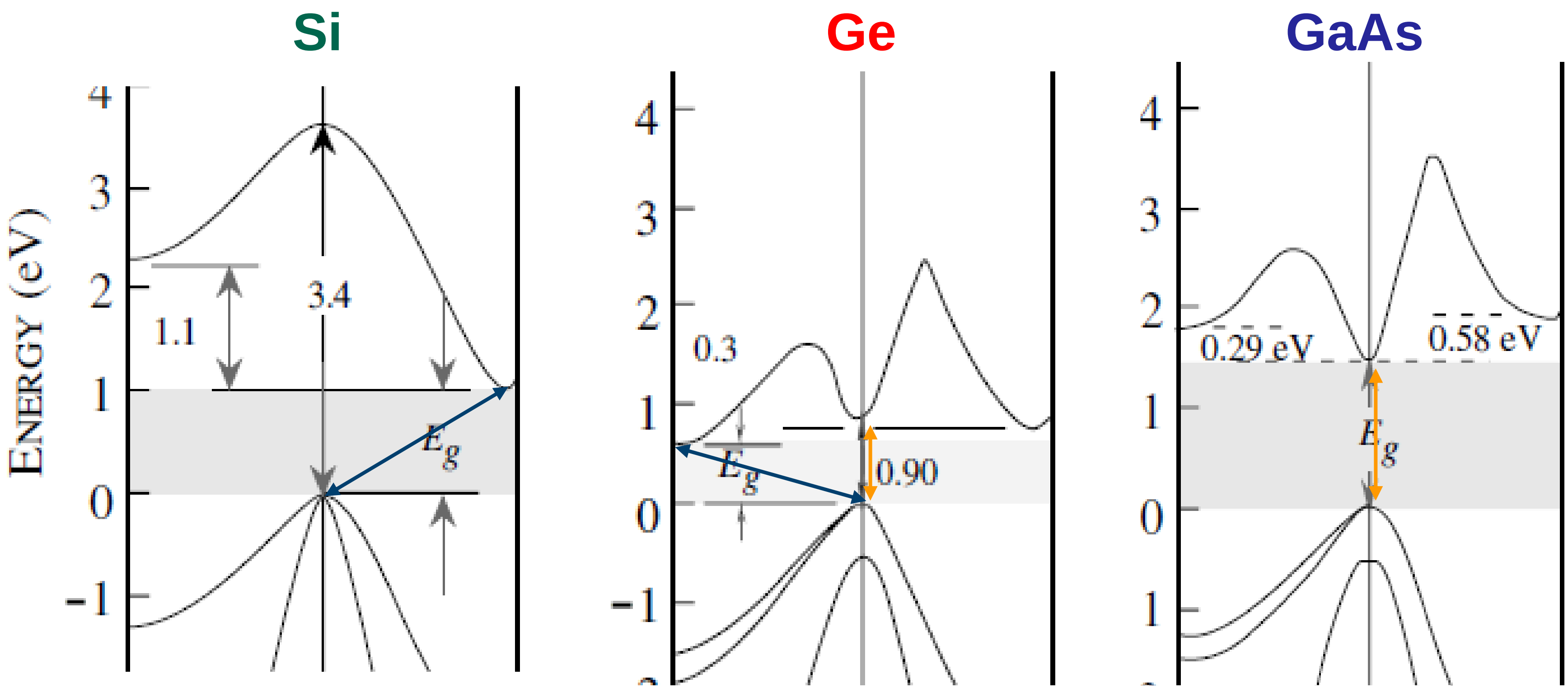
band-to-band transitions



band-to-band transitions

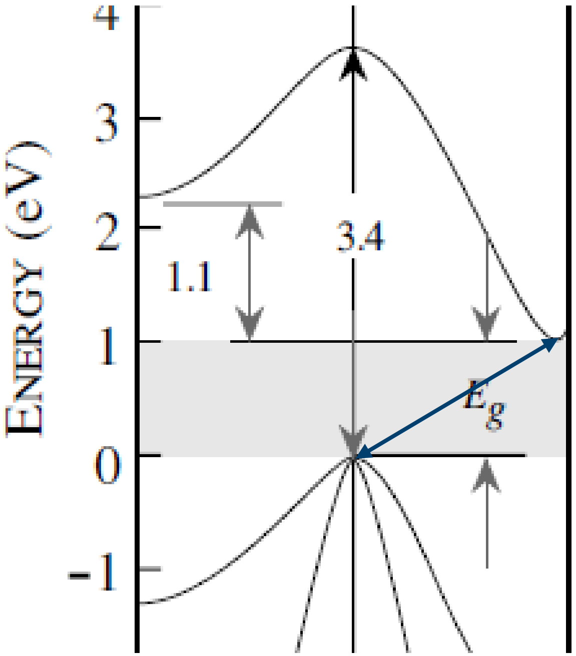


band-to-band transitions



band-to-band transitions --- spin properties

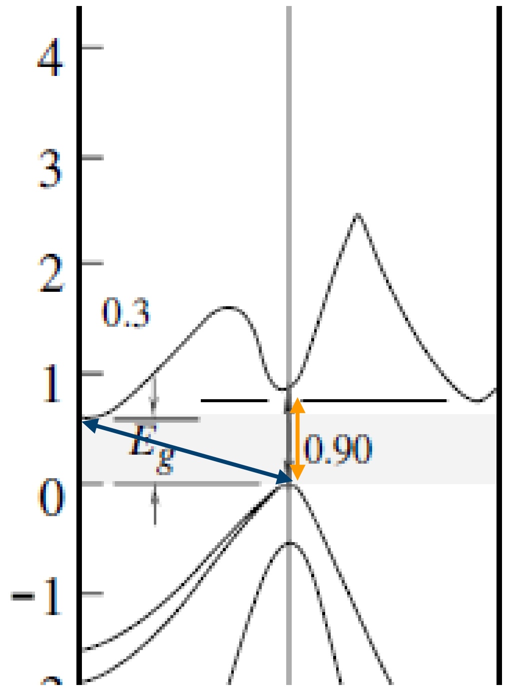
Si



$\tau_s \approx 100$ ns

$\ell_s \approx 100\ \mu m$

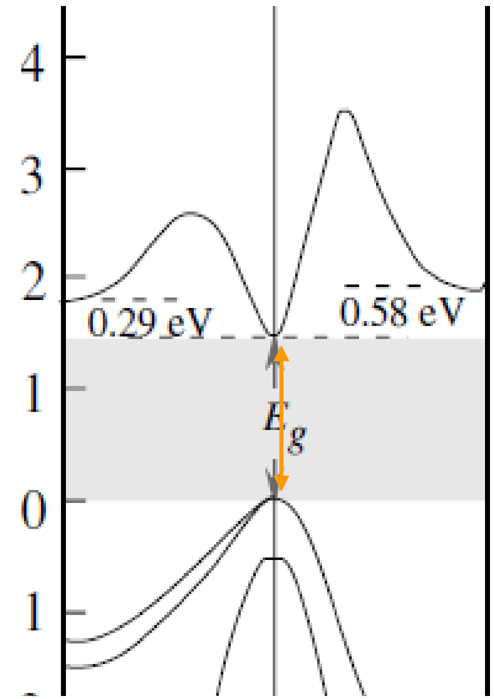
Ge



$\tau_s \approx 1$ ns

$\ell_s \approx 1\ \mu$ m

GaAs



$\tau_s \approx 0.1$ ns

$\ell_s \approx 0.1\ \mu m$

@ **RT**

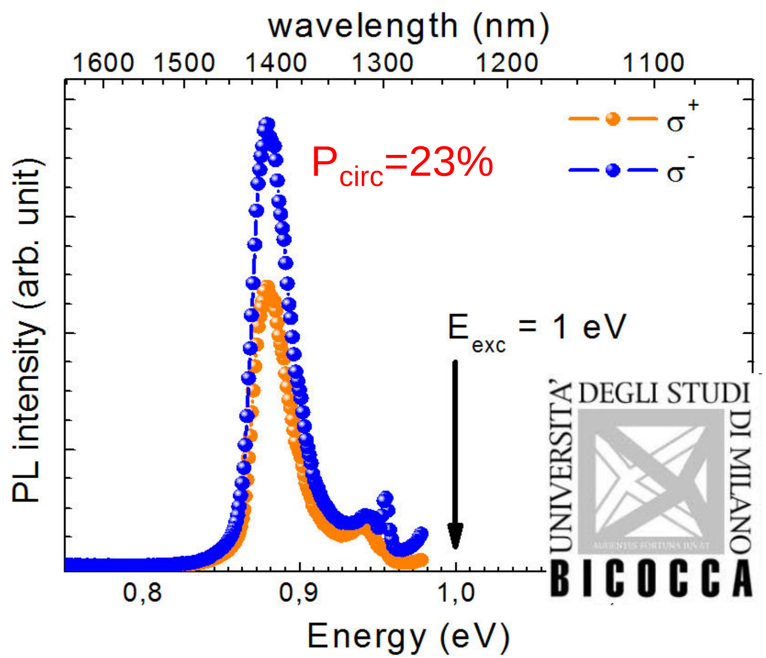
Spin in group IV semiconductors

G. Lampel, Phys. Rev. Lett. 20, 491 **(1968)**
Nuclear dynamic polarization by optical electronic saturation and optical pumping in semiconductors, **(Si)**

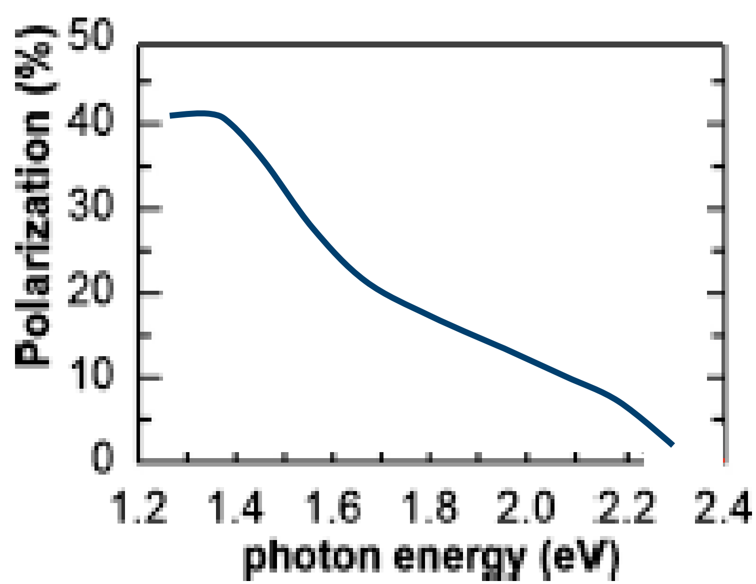
R. Allenspach, F. Meier, and D. Pescia, *Phys. Rev. Lett.* 51, 2148 **(1983)**
Experimental Symmetry Analysis of Electronic States by Spin-Dependent Photoemission **(Ge)**

bulk Ge (2011, our group)

Polarixed luminesce

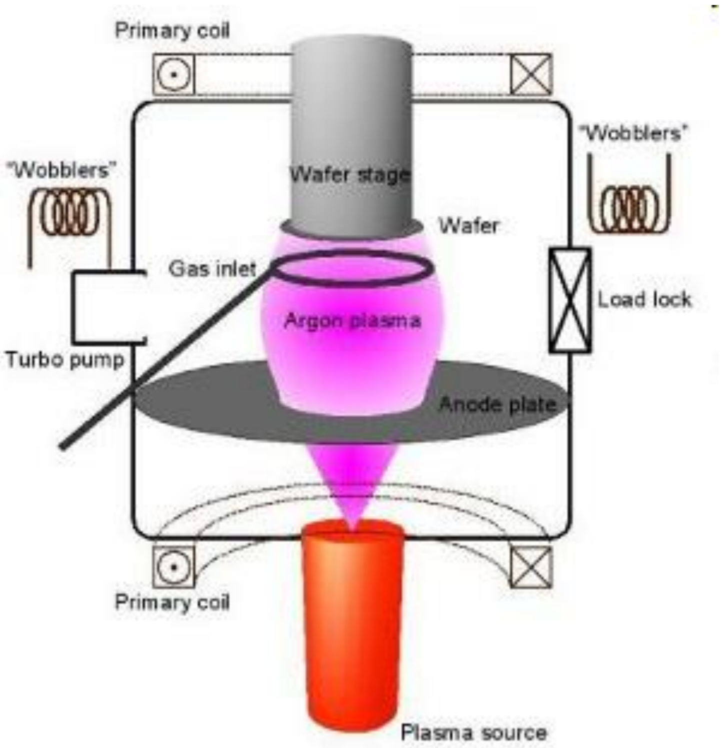


Polarized Photoemission



sample growth (group IV)

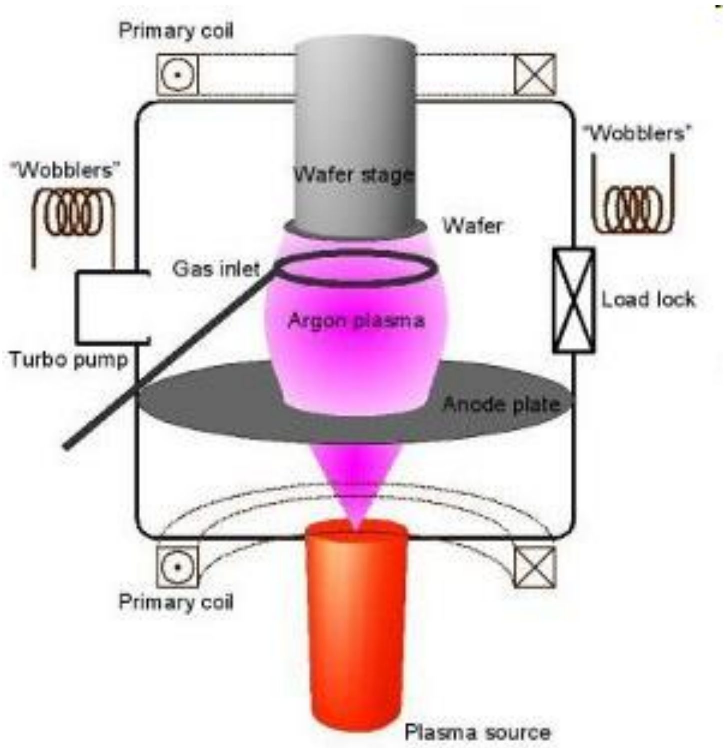
LEPECVD: Low Energy Plasma Enanched Chemical Vapor Deposition



G. Isella, D. Chrastina, B. Rössner, T. Hackbarth,H.-J. Herzog, U. König, H. von Känel, Solid-State Electron. 48, 1317 (2004)

sample growth (group IV)

LEPECVD: Low Energy Plasma Enanched Chemical Vapor Deposition



- High density - low energy plasma

  no ion induced damage → epitaxy
- Deposition rate independent on substrate temperature

  control of surface diffusion lenght
- wide range of deposition rates

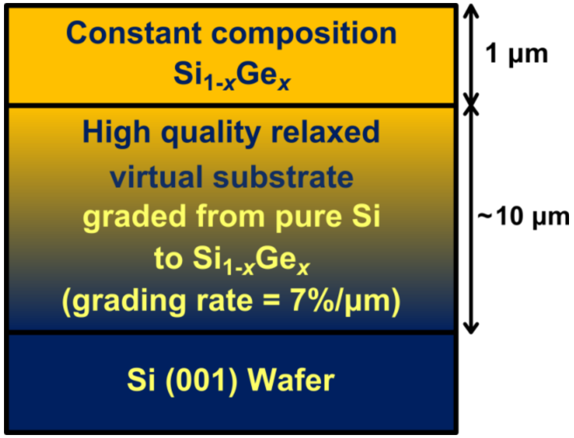
  from 0.1 to 10 nm/s
- limited effects of surface chemistry

  good control of film composition

G. Isella, D. Chrastina, B. Rössner, T. Hackbarth,H.-J. Herzog, U. König, H. von Känel, Solid-State Electron. 48, 1317 (2004)

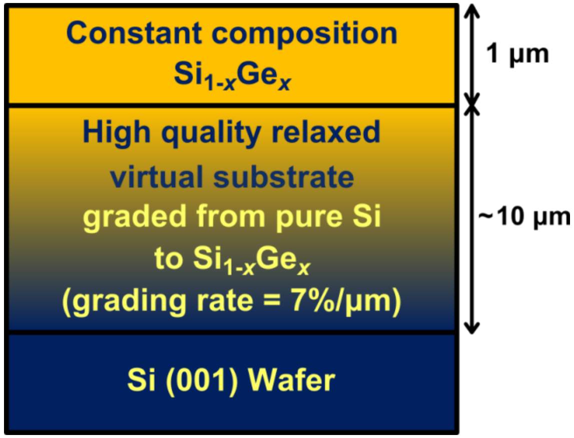
high quality Ge-based nanostructures

Bulk-like alloys

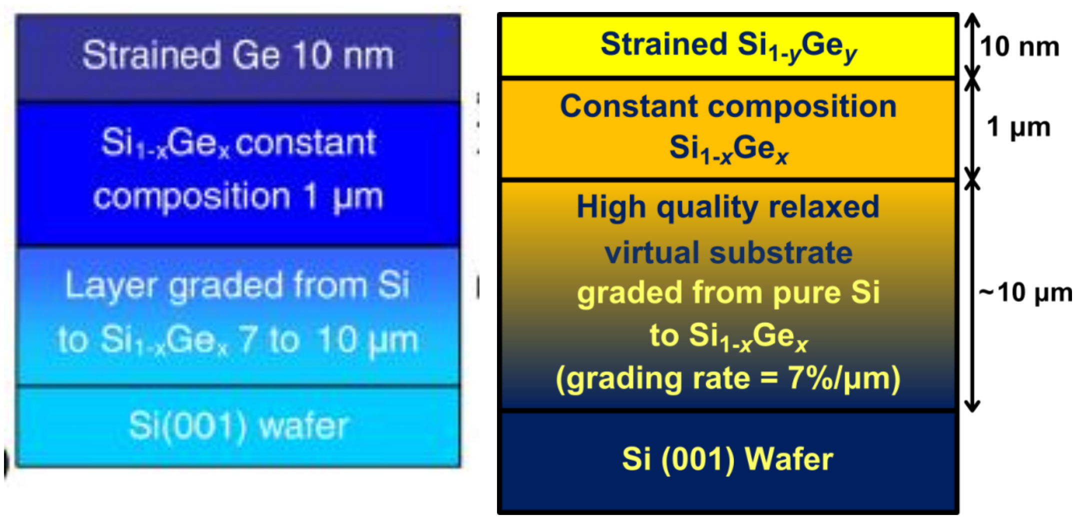


high quality Ge-based nanostructures

Bulk-like alloys

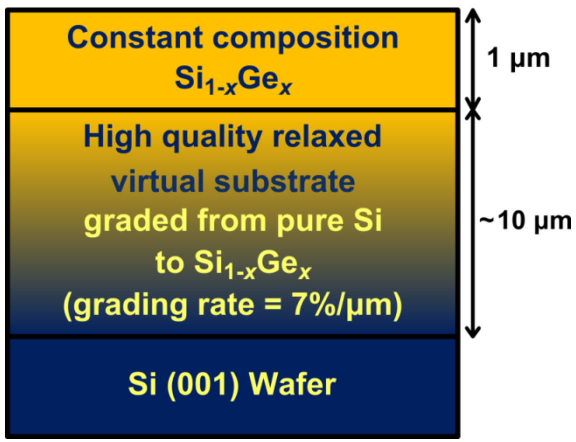


Strained thin films

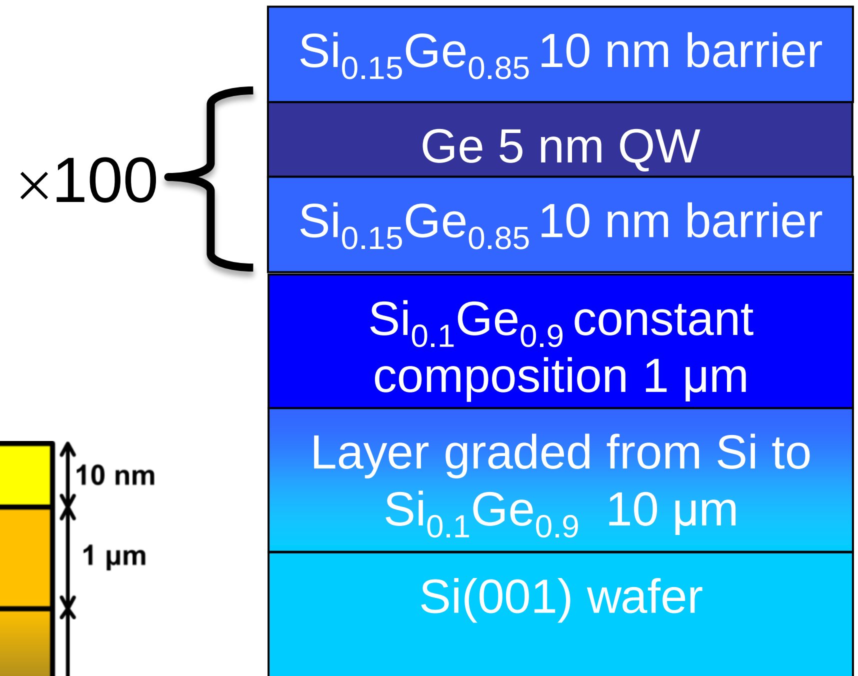


high quality Ge-based nanostructures

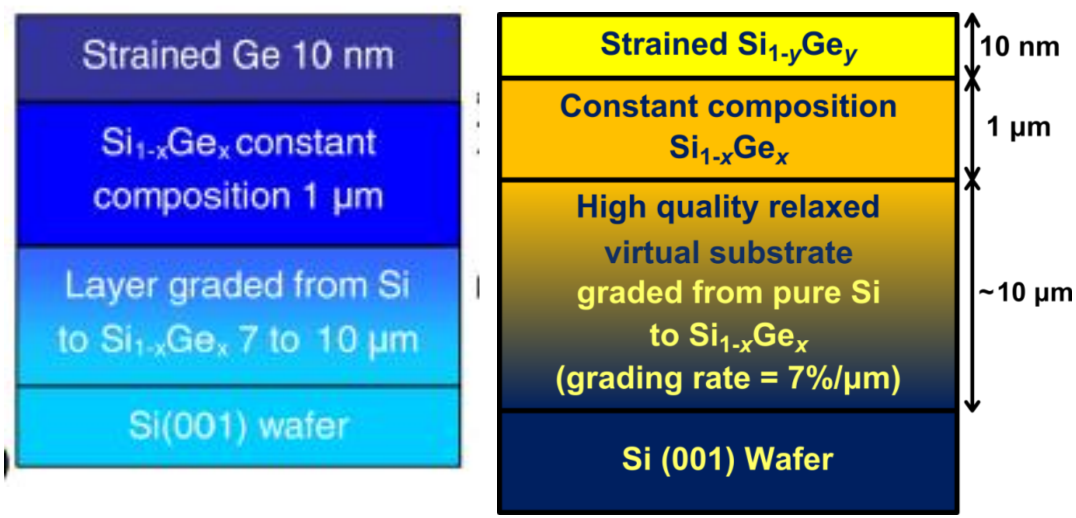
Bulk-like alloys



Multiple Quantum Wells



Strained thin films



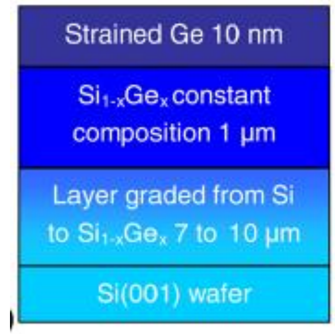
Strained thin films

APPLIED PHYSICS LETTERS **98**, 242107 (2011)

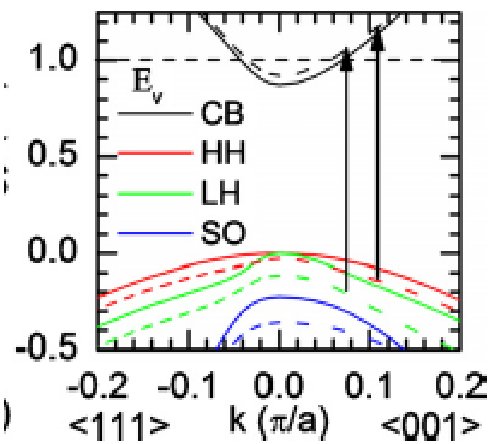
Spin polarized photoemission from strained Ge epilayers

Federico Bottegoni, Giovanni Isella,[a)] Stefano Cecchi, and Franco Ciccacci
Dipartimento di Fisica, LNESS, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy

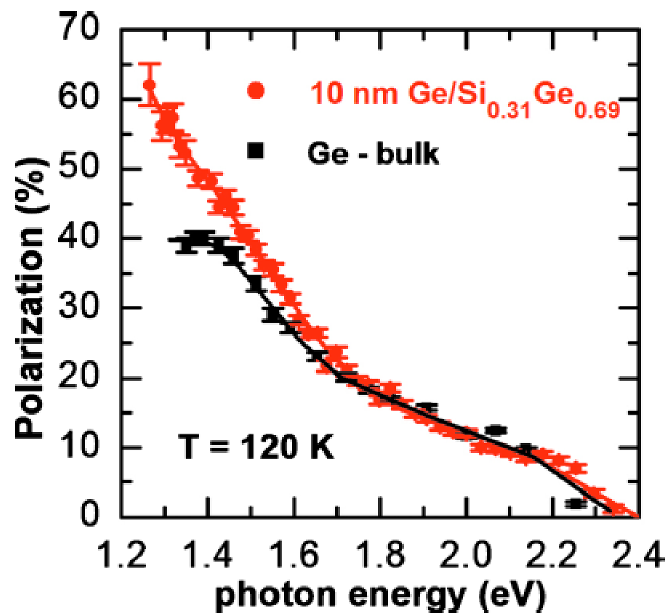
(Received 7 April 2011; accepted 21 May 2011; published online 14 June 2011)



We report on spin polarized electron photoemission experiments on compressively strained Ge/SiGe/Si(001) layers. Spin polarization of conduction band electrons up to $P=62\%$ at $T=120$ K has been observed, well above the theoretical limit of $P=50\%$ valid for bulk materials. Such spin polarization increase, can be attributed to the strain-induced removal of the heavy-hole light-hole degeneracy in the valence band. A set of Ge epilayers with different strain levels has been characterized, achieving an experimental correlation between the measured polarization and the strain in the epilayer. © *2011 American Institute of Physics*. [doi:10.1063/1.3599493]



- Strain increases P
- P>50% bulk-limit



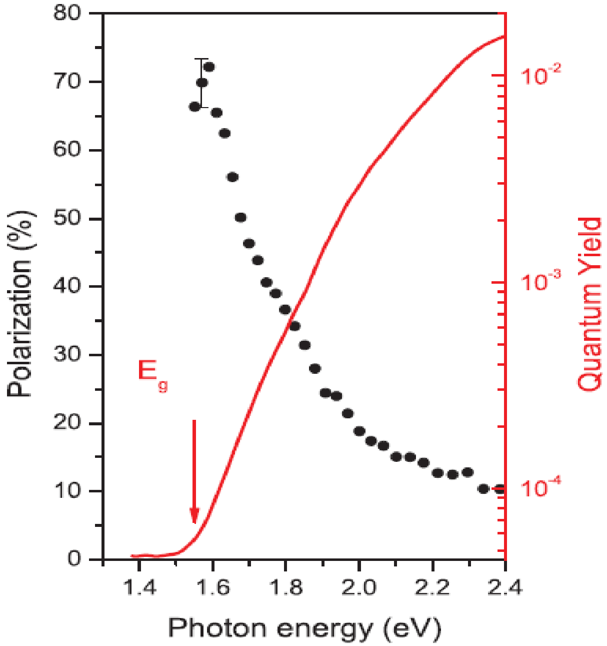
Strained thin films

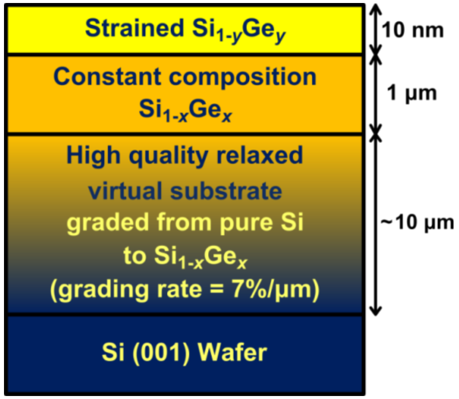
PHYSICAL REVIEW B **88**, 115209 (2013)

Epitaxial $Si_{1-x}Ge_x$ alloys studied by spin-polarized photoemission

A. Ferrari,* F. Bottegoni, G. Isella, S. Cecchi, and F. Ciccacci
LNESS-Dipartimento di Fisica, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy
(Received 10 June 2013; revised manuscript received 3 September 2013; published 20 September 2013)

Spin-polarized photoemission is used to study $Si_{1-x}Ge_x$ alloys epitaxially grown on a Si substrate. Spin-oriented electrons are generated in the conduction band upon excitation with circularly polarized light. We prove that in these structures it is possible to lower the vacuum level of the system below the conduction band minimum at the Γ point of the Brillouin zone and show that electron spin polarization values $P = 40 \pm 3\%$ can be achieved when promoting electrons with direct transitions at Γ. Such values can be greatly increased, up to $P = 72 \pm 3\%$, in compressively strained thin epitaxial films, thus obtaining performances very close to those of III-V semiconductor heterostructures.





Strained thin films

PHYSICAL REVIEW B 88, 115209 (2013)

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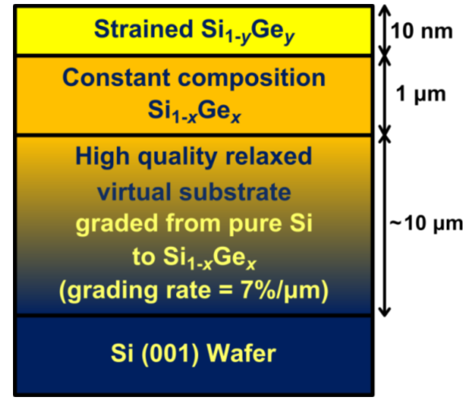

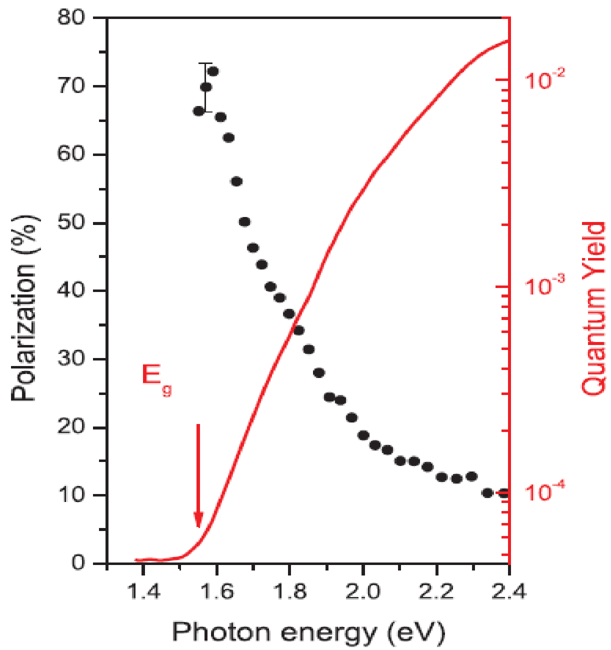

$P = 72 \pm 3\%$ in compressively strained SiGe

High spin-oriented population at CB bottom

Comparable with III-V strained layers

Polarized luminescence: SiGe/Ge QW

PRL **108,** 156603 (2012) PHYSICAL REVIEW LETTERS week ending 13 APRIL 2012

Optical Spin Injection and Spin Lifetime in Ge Heterostructures

F. Pezzoli,[1,*] F. Bottegoni,[2] D. Trivedi,[3] F. Ciccacci,[2] A. Giorgioni,[1] P. Li,[4] S. Cecchi,[2] E. Grilli,[1] Y. Song,[3] M. Guzzi,[1] H. Dery,[3,4] and G. Isella[2]

[1]*LNESS–Dipartimento di Scienza dei Materiali, Università degli Studi di Milano-Bicocca, I-20125 Milano, Italy*
[2]*LNESS–Dipartimento di Fisica, Politecnico di Milano, I-20133 Milano, Italy*
[3]*Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627, USA*
[4]*Department of Electrical and Computer Engineering, University of Rochester, Rochester, New York 14627, USA*
(Received 29 June 2011; revised manuscript received 15 November 2011; published 13 April 2012)

We demonstrate optical orientation in Ge/SiGe quantum wells and study their spin properties. The ultrafast electron transfer from the center of the Brillouin zone to its edge allows us to achieve high spin polarizations and to resolve the spin dynamics of holes and electrons. The circular polarization degree of the direct gap photoluminescence exceeds the theoretical bulk limit, yielding ~37% and ~85% for transitions with heavy and light holes states, respectively. The spin lifetime of holes at the top of the valence band is estimated to be ~0.5 ps and it is governed by transitions between light and heavy hole states. Electrons at the bottom of the conduction band, on the other hand, have a spin lifetime that exceeds 5 ns below 150 K. Theoretical analysis of the spin relaxation indicates that phonon-induced intervalley scattering dictates the spin lifetime of electrons.

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

Polarized luminescence: SiGe/Ge QW

PRL **108**, 156603 (2012) PHYSICAL REVIEW LETTERS week ending 13 APRIL 2012

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[1]*LNESS–Dipartimento di Scienza dei Materiali, Università degli Studi di Milano-Bicocca, I-20125 Milano, Italy*
[2]*LNESS–Dipartimento di Fisica, Politecnico di Milano, I-20133 Milano, Italy*

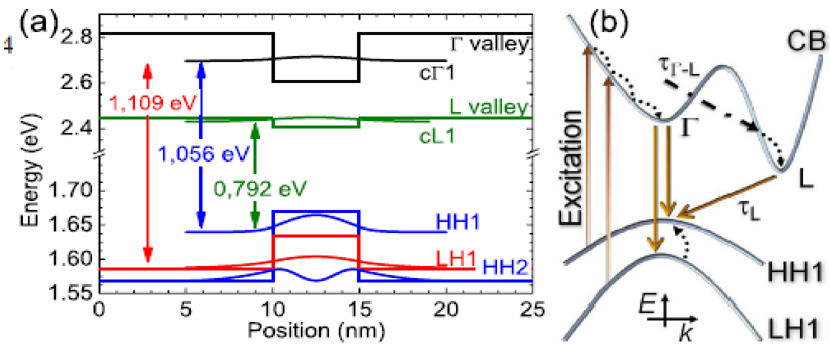
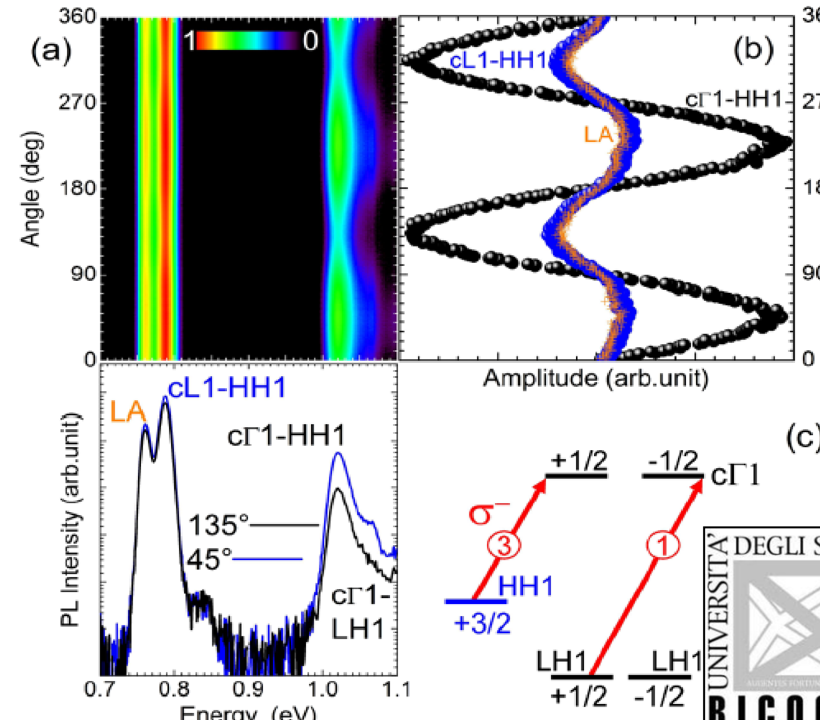


FIG. 1 (color online). (a) 8-band **k · p** calculation of energy levels and wave function square amplitudes for a $Si_{0.15}Ge_{0.85}/Ge/Si_{0.15}Ge_{0.85}$ quantum well. (b) Sketch of the luminescence process. Immediately after direct gap excitation, electrons can thermalize towards the edge of the Γ valley and recombine radiatively. For Γ valley electrons, however, the most effective process is scattering to the low-energy L valleys, where they can recombine after τ_L. The ultrafast time scale $\tau_{\Gamma\text{-}L} < 1$ ps sets the lifetime for electrons at Γ.



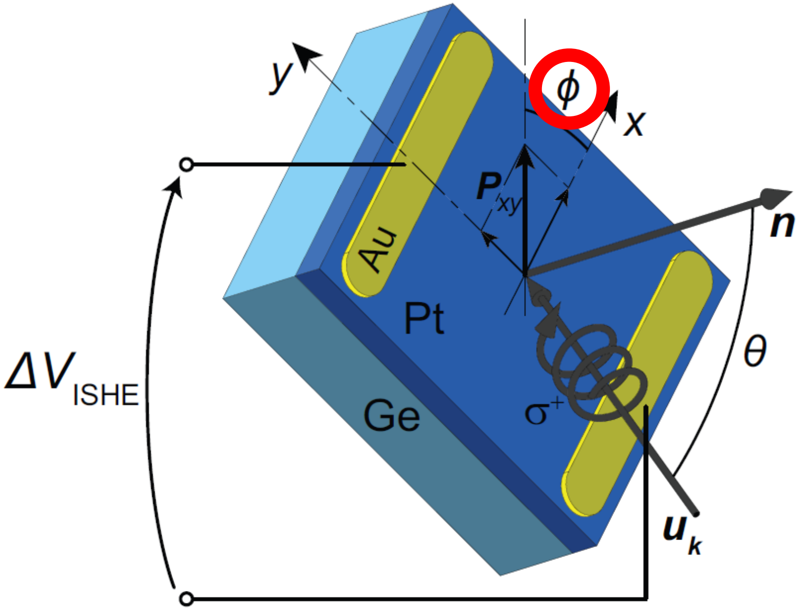
UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

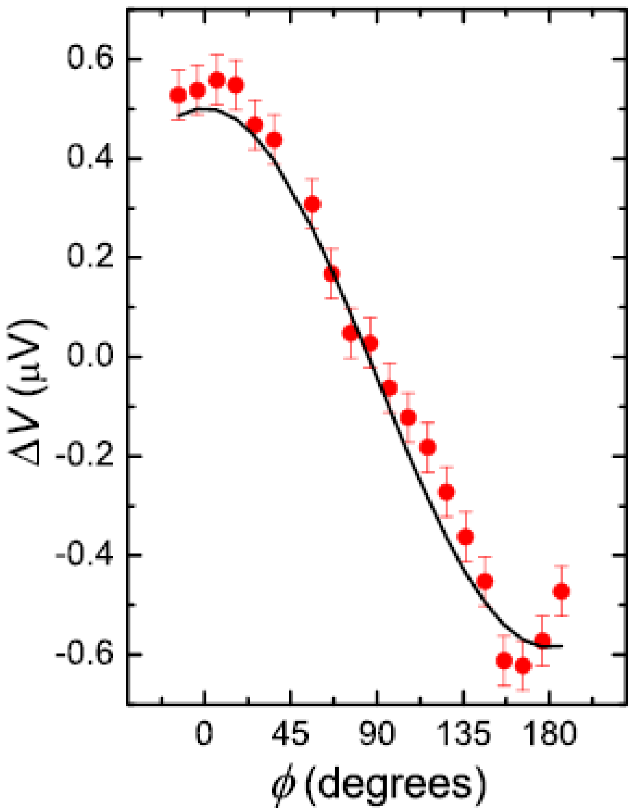
Optical ISHE: Pt/Ge(001)

APPLIED PHYSICS LETTERS **102**, 152411 (2013)

Photoinduced inverse spin Hall effect in Pt/Ge(001) at room temperature

F. Bottegoni,[a)] A. Ferrari, S. Cecchi, M. Finazzi, F. Ciccacci, and G. Isella
LNESS-Dipartimento di Fisica, Politecnico di Milano, Piazza Leonardo da Vinci 32, 2013





Sample: <u>Pt/Ge junction</u> (5 x 5 mm²)

- **4 nm-thick Pt-layer**
- **450 μm-thick As-doped Ge (N_D =1.7 x10^{16} cm^{-3})**
- **50 nm-thick Au electrodes**

$\Delta V_{ISHE} \approx \cos \phi$

Optical ISHE: Pt/Ge(001)

APPLIED PHYSICS LETTERS **102**, 152411 (2013)

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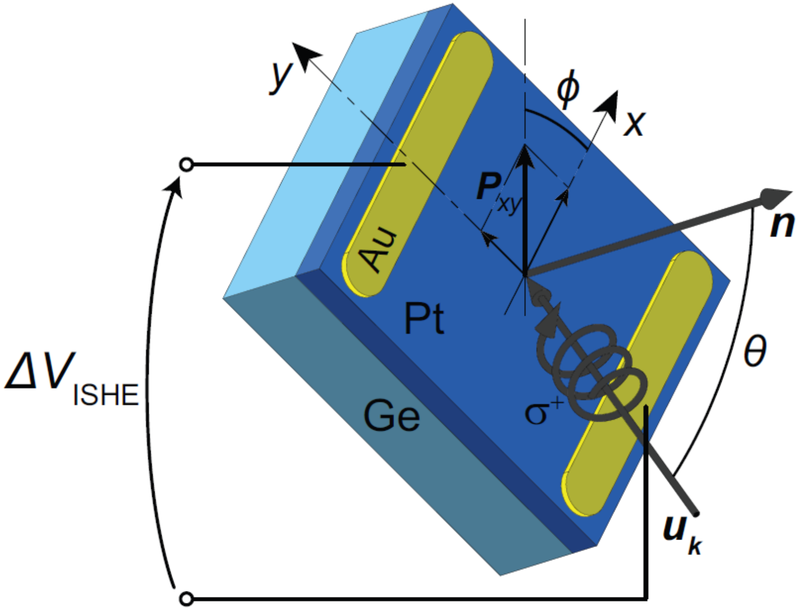
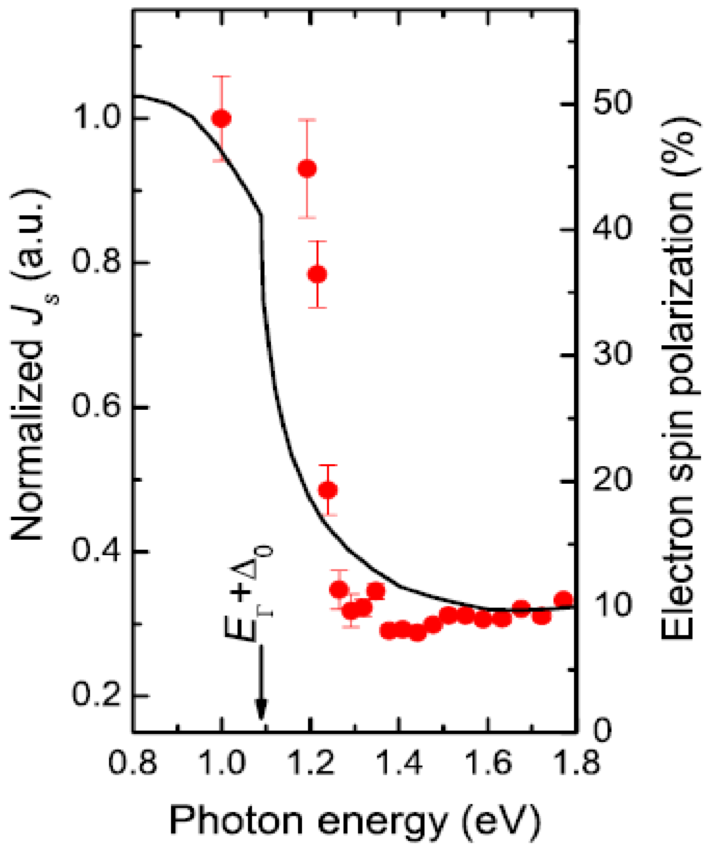




Sample: Pt/Ge junction (5 x 5 mm²)

- **4 nm-thick Pt-layer**
- **450 µm-thick As-doped Ge (N_D =1.7 x10^{16} cm^{-3})**
- **50 nm-thick Au electrodes**

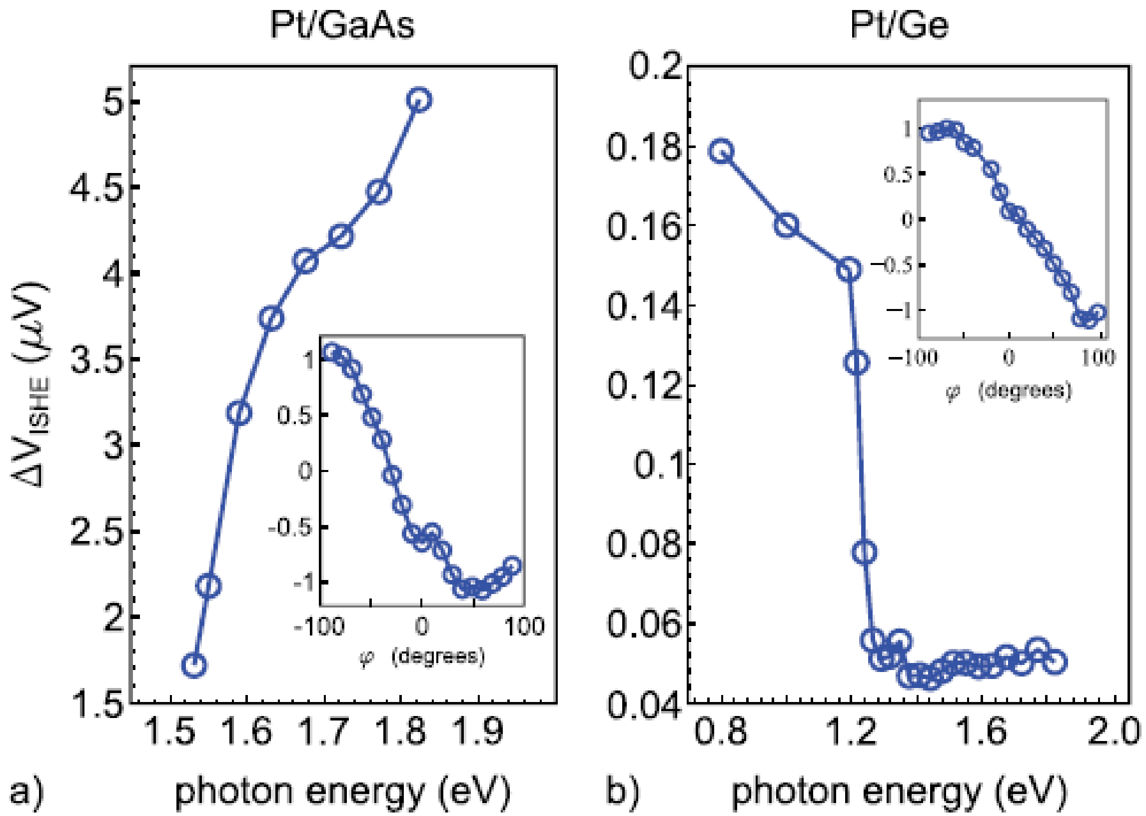
J_s is proportional to P

ISHE *versus* hν

APPLIED PHYSICS LETTERS **106**, 232402 (2015)

Photon energy dependence of photo-induced inverse spin-Hall effect in Pt/GaAs and Pt/Ge

Giovanni Isella,[a)] Federico Bottegoni, Alberto Ferrari, Marco Finazzi, and Franco Ciccacci
LNESS-Dipartimento di Fisica, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy



ISHE *versus* hν

APPLIED PHYSICS LETTERS **106**, 232402 (2015)

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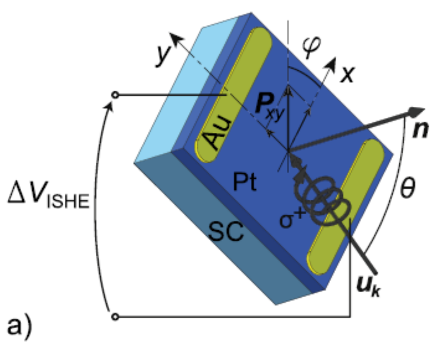
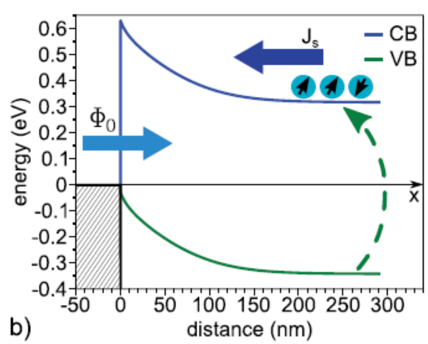
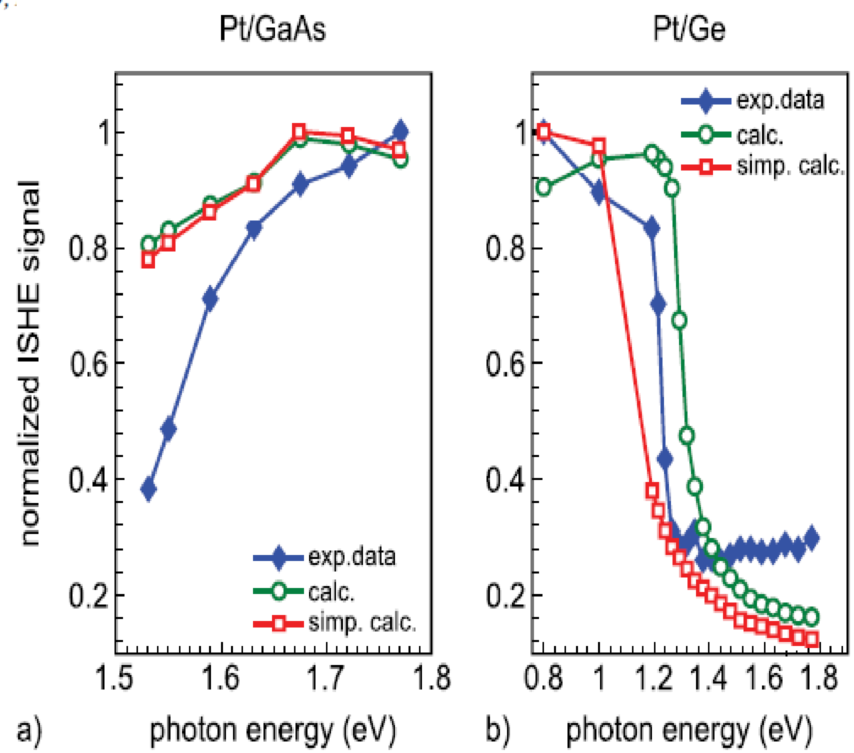






Spin-drift diffusion model

$$\frac{1}{q} J_s = -D_n \frac{\partial s}{\partial x} - \mu_n s E(x),$$

$$\frac{1}{q} \frac{\partial J_s}{\partial x} = \frac{s}{\tau_s} - w(x) s p + P \Phi_0 \alpha e^{-\alpha x},$$

$\tau_{GaAs} \sim 10^{-11}$ s → $\alpha L_s < 1$

$\tau_{Ge} \sim 10^{-9}$ s → $\alpha L_s > 1$

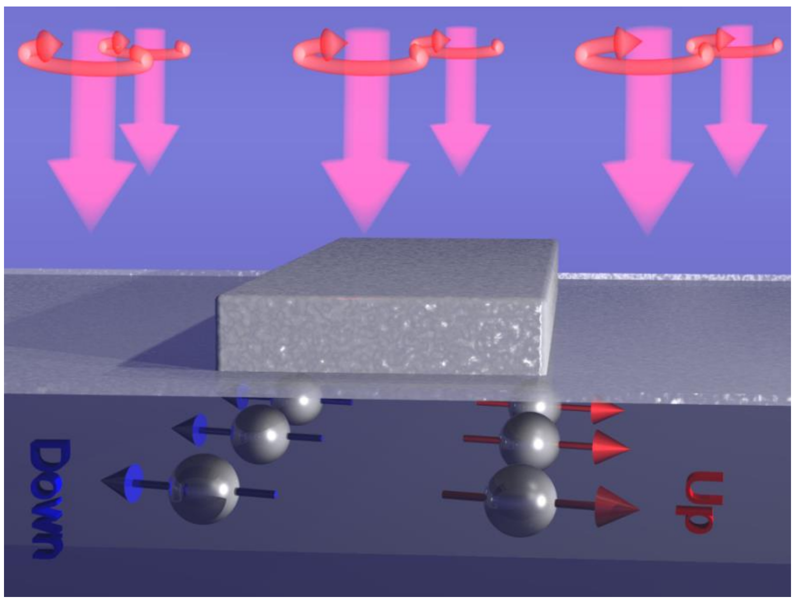
Spin photovoltaic cell

Spin voltage generation through optical excitation of complementary spin populations

F. Bottegoni, M. Celebrano, M. Bollani, P. Biagioni, G. Isella, F. Ciccacci, M. Finazzi

NATURE MATERIALS | VOL 13 | JULY 2014 | www.nature.com/naturematerials

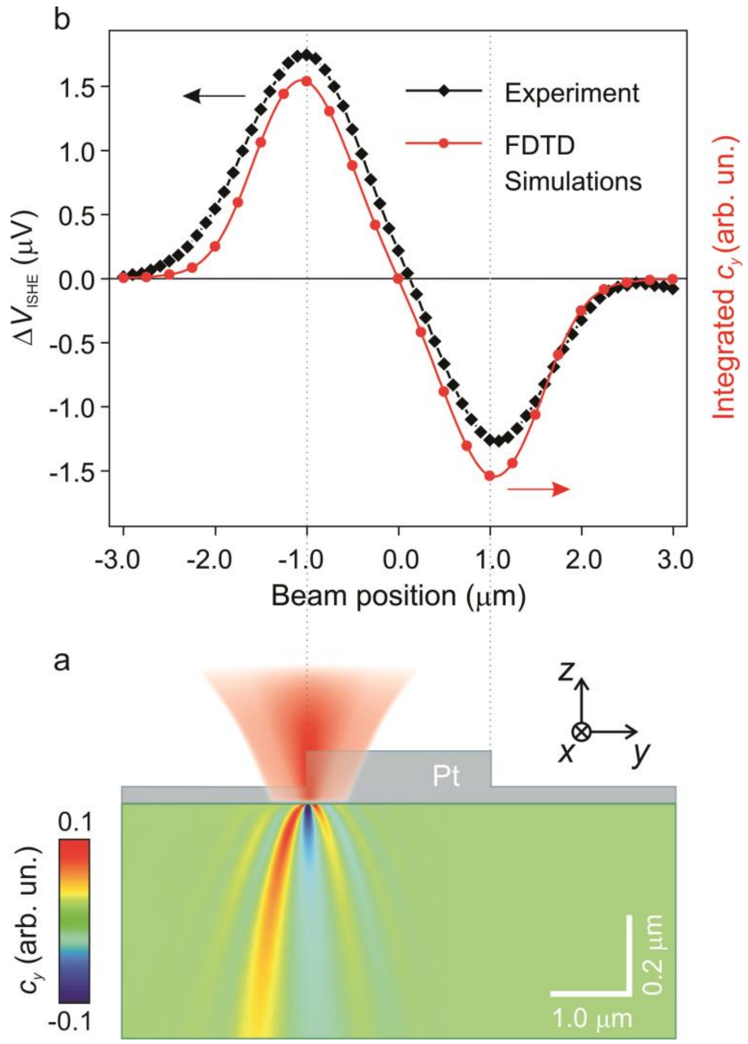
In plane spin orientation at normal incidence



- patterning a thin overlayer onto the semiconductor surface
- spatially modulating the phase and amplitude of the em wave-front
- normal incidence operation

LETTERS
PUBLISHED ONLINE: 22 JUNE 2014 | DOI: 10.1038/NMAT4015
nature materials

Patterned Pt film on Ge - modelling



Full vectorial three-dimensional electromagnetic simulations

performed by the finite-difference time-domain (FDTD) approach,

(FDTD Solutions, version 8.5.3, Lumerical Inc. Vancouver, Canada).

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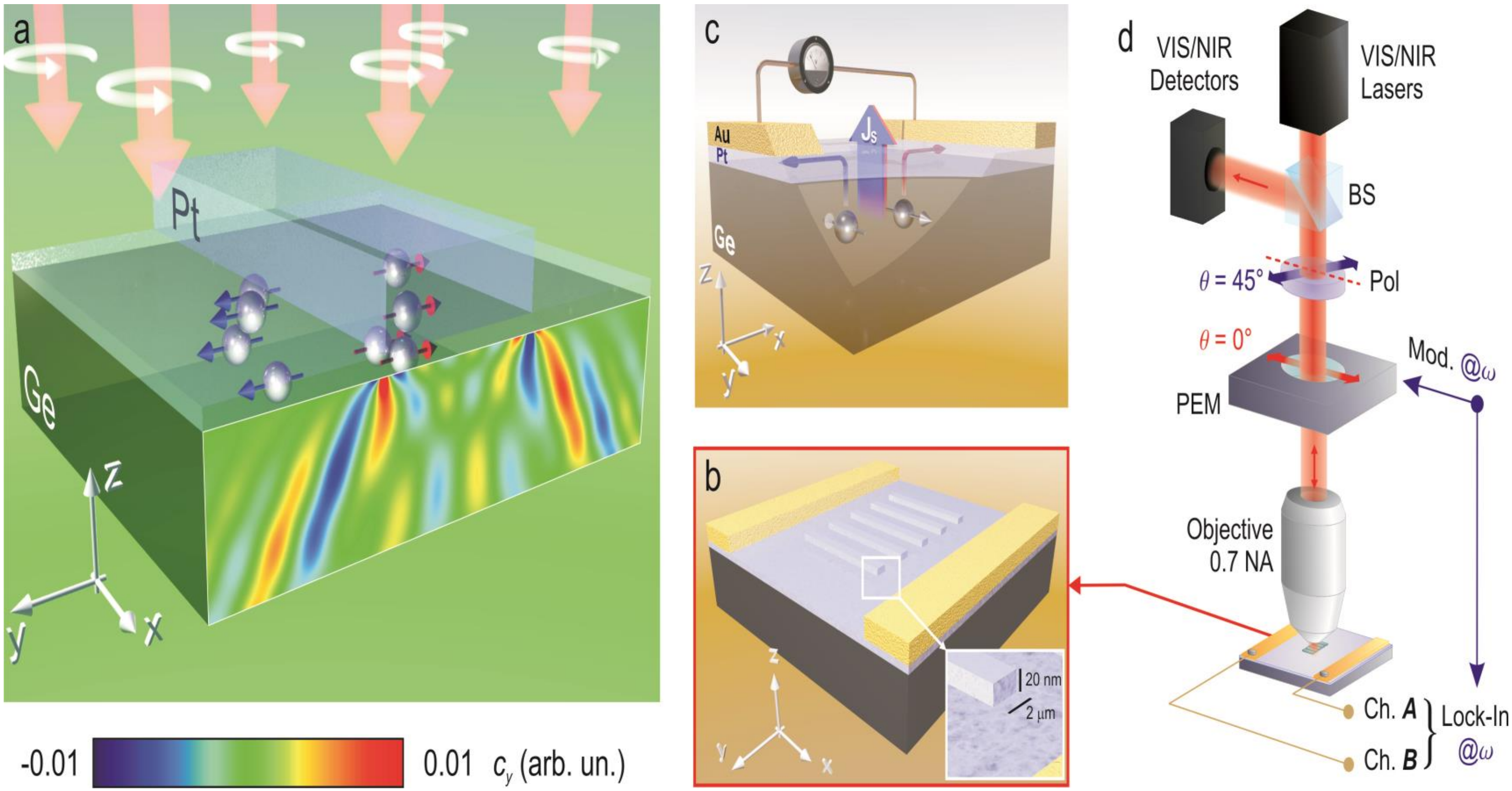
Spatially-resolved ISHE: principles and set-up



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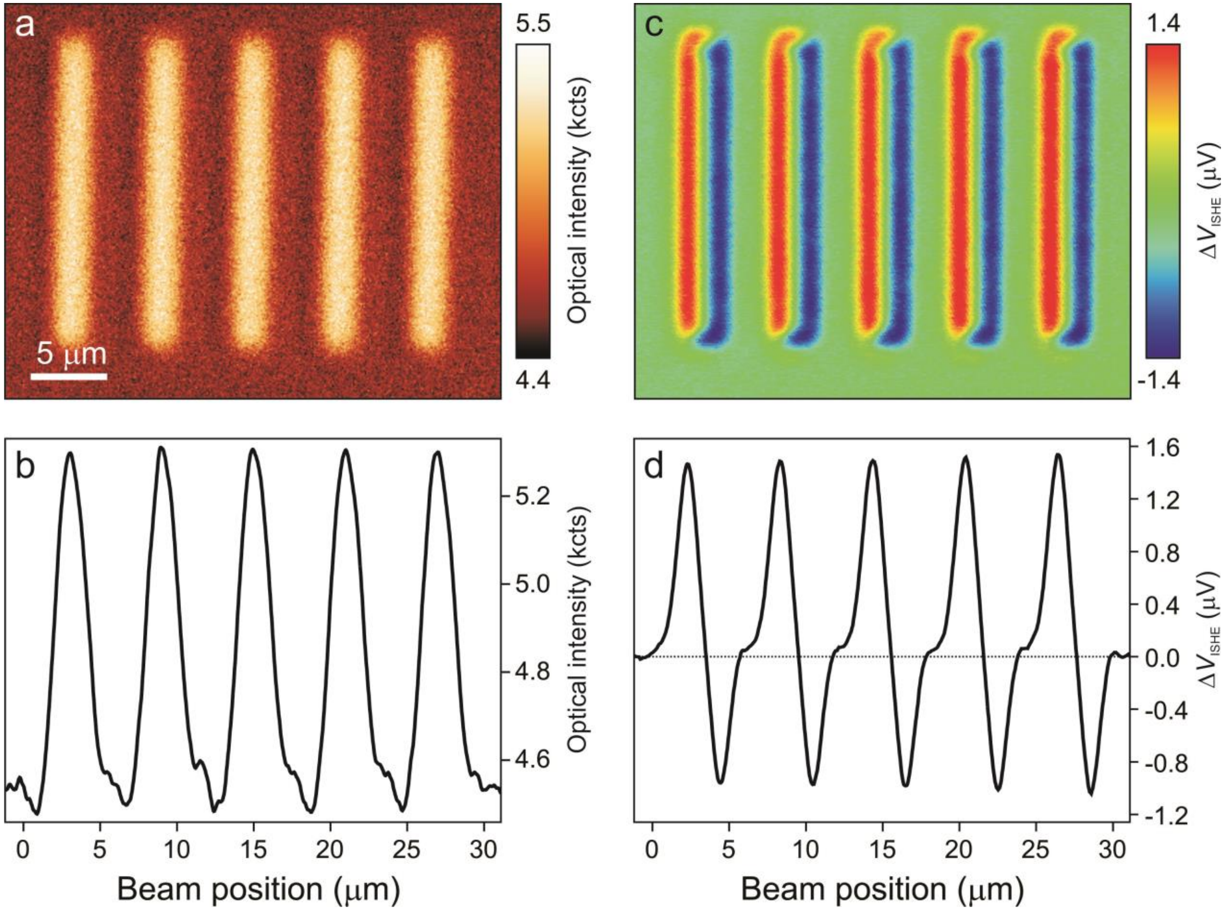
Optical spin injection and detection through ISHE

2D map

horizontal profile



optical reflectivity
(InGaAs detector)

differential voltage signal ΔV_{ISHE}
(exciting photon energy *hv* = 0.8 eV, incident power *W* = 150 µW)

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Pure spin current generator

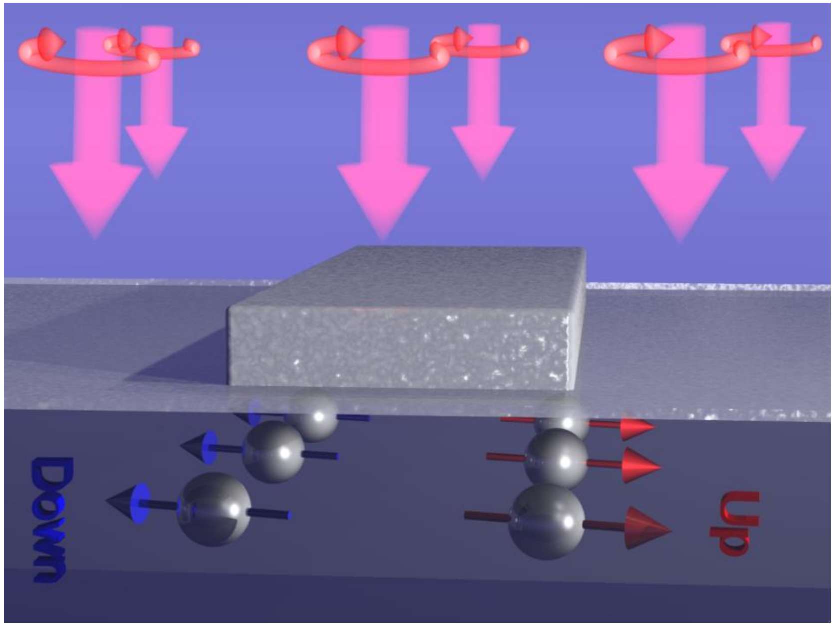


Fig. 2. Spin voltage generator, consisting in a Pt strip evaporated on a Ge wafer. Upon illumination with circularly polarized light spin-up (red arrows) or spin-down (blue arrows) accumulation is obtained [13].

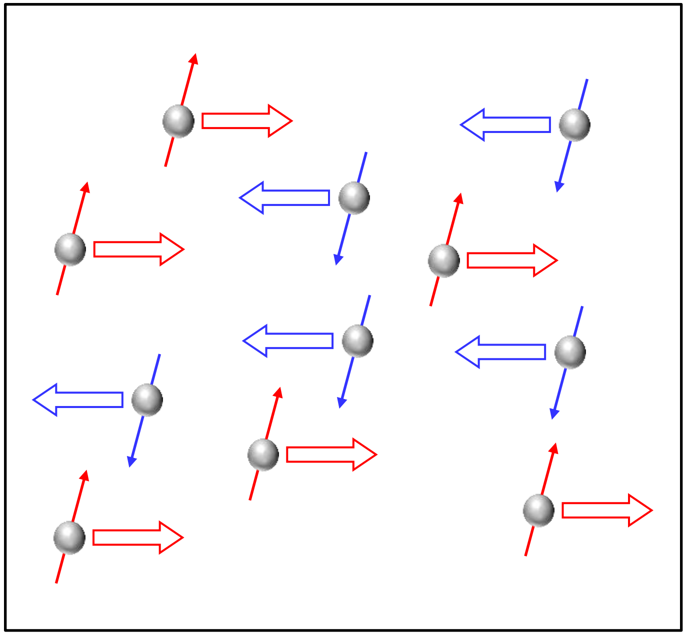
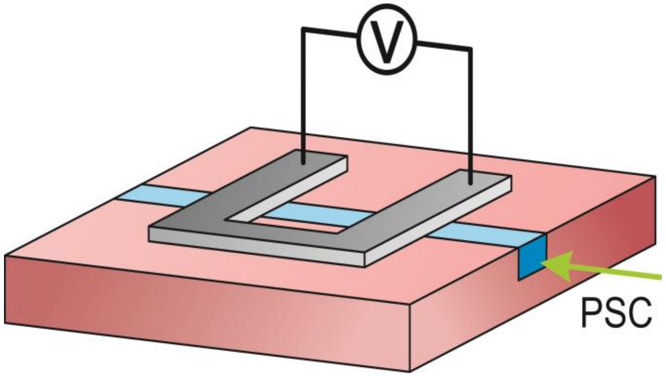


Fig. 1. A pure spin current is constituted by electrons with spin-up (thin red arrows) polarization moving with velocities (indicated by the hollow red arrows) pointing in one direction superposed to an equal amount of electrons with spin-down (thin blue arrows) polarization flowing in the opposite direction (hollow blue arrows).

Applications ??



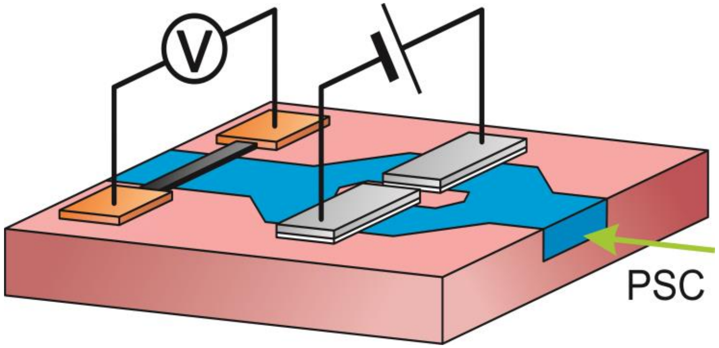


Fig. 1. Proposal for an ISHE sensor able to directly measure a spin-voltage drop. In each arm of the U-shaped structure an ISHE electromotive field is induced, resulting in a voltage drop proportional to the spin-polarization of carriers in the semiconductor beneath each arm. Measuring the total voltage drop when the two arms are connected in series, as in the figure, will deliver a signal proportional to the difference between the ISHE electromotive fields in the two arms, in turn proportional to the spin-voltage drop in the semiconductor.

Fig. 3. Proposal for a device to evaluate interference between PSCs. A PSC is split in two channels where different bias are applied. The resulting spin accumulation (or PSC intensity) when the two PSCs are recombined in the same node is evaluated by measuring the electromotive field induced across an ISHE sensor.

SemiSpin (Spin in Semiconductors) group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L. Duo
A. Picone
G. Cerullo
S. Dal Conte
R. Bertacco
J. Frigerio
M. Bollani

M. Celebrano
A. Calloni
A. Brambilla
GL. Bussetti
C. Rinaldi
M. Cantoni

F. Pezzoli
E. Gatti
E. Grilli
M. Guzzi

M. Janet
A. Ferrari
A. Marty
C. Vergnaud