Concept of projection-type 3D spin-resolving electron detector with spatial resolution and new type of polarized electron source

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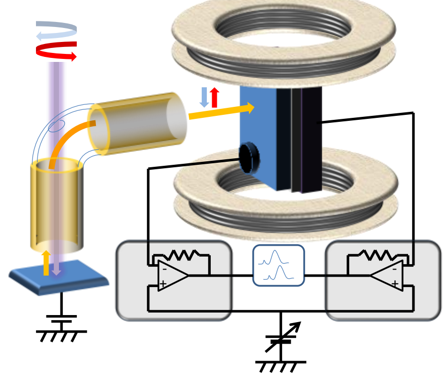
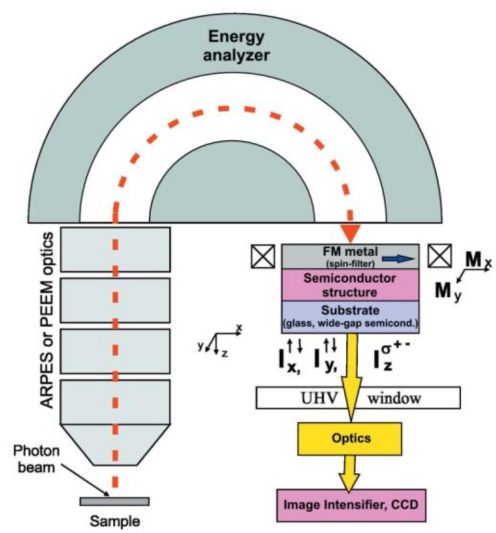
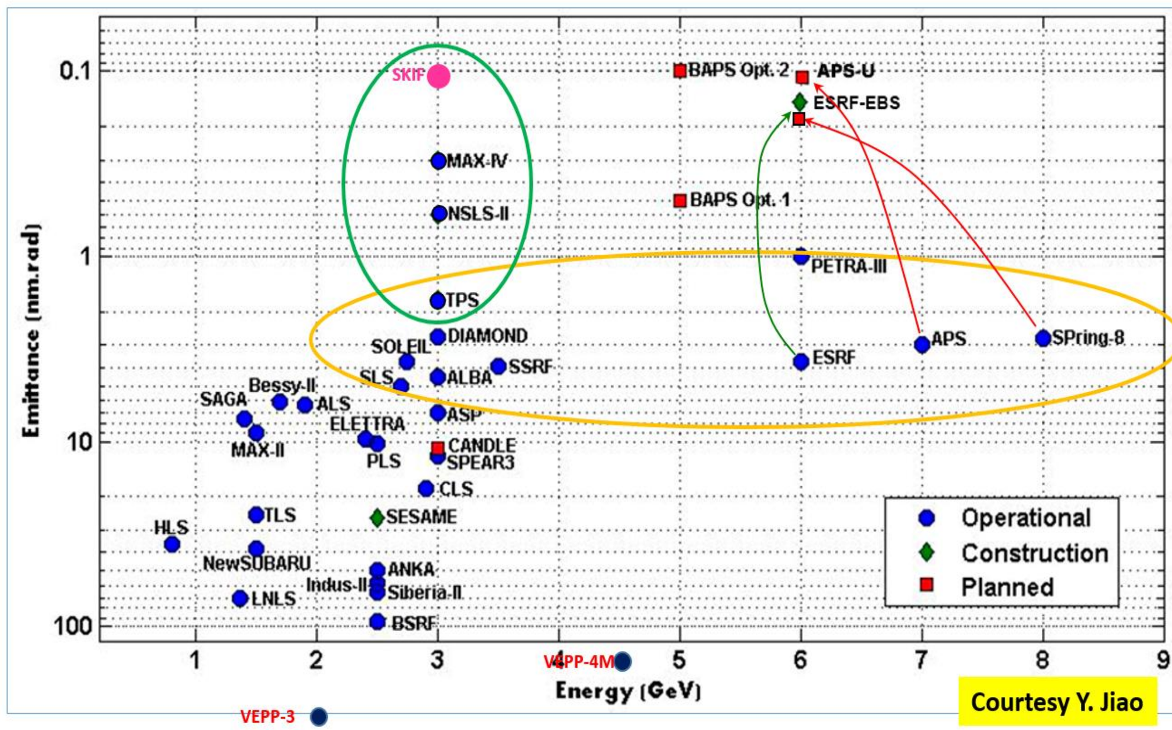




SRF “SKIF” general information

Fourth generation synchrotron radiation source

Parameter	Value
Energy	3 GeV
Current	Up to 400 mA
Emittance	60 - 90 pm·rad
Injection type	Full injection
Perimeter	476m
Number of experimental stations	6 (first stage) +24 (second stage)
Number of IDs	14

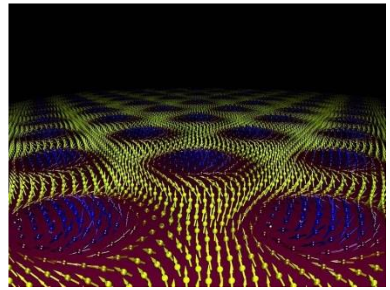


Spin- and Angle-resolved photoemission spectroscopy (SARPES) allows to study

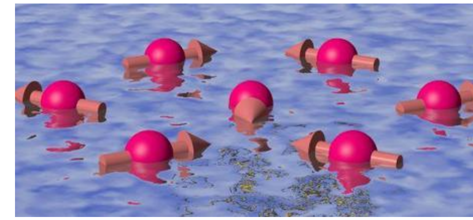
Many phenomena in quantum materials

Structures in momentum space

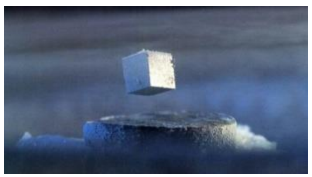
- Brillouin zones
- Fermi surfaces
- Band dispersion



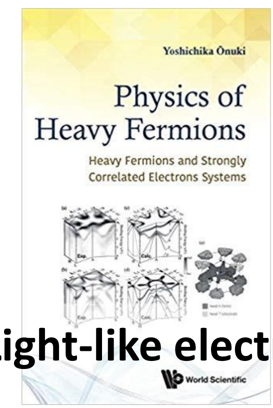
Various types of magnetic order



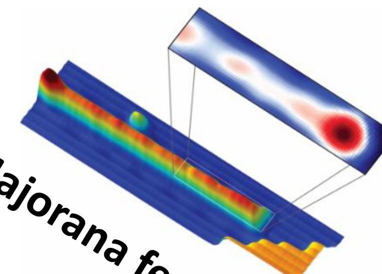
Quantum spin liquids



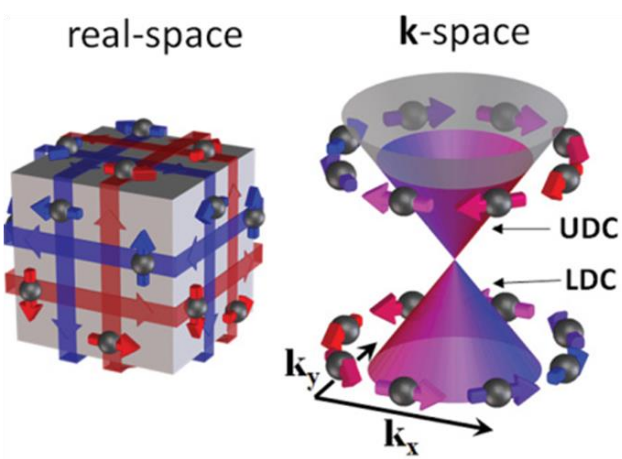
Superconductivity



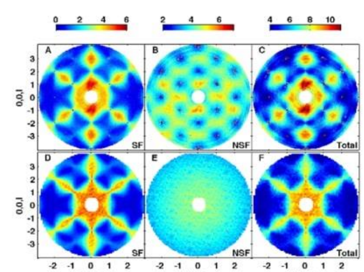
Light-like electrons



Majorana fermions



Topological Insulators

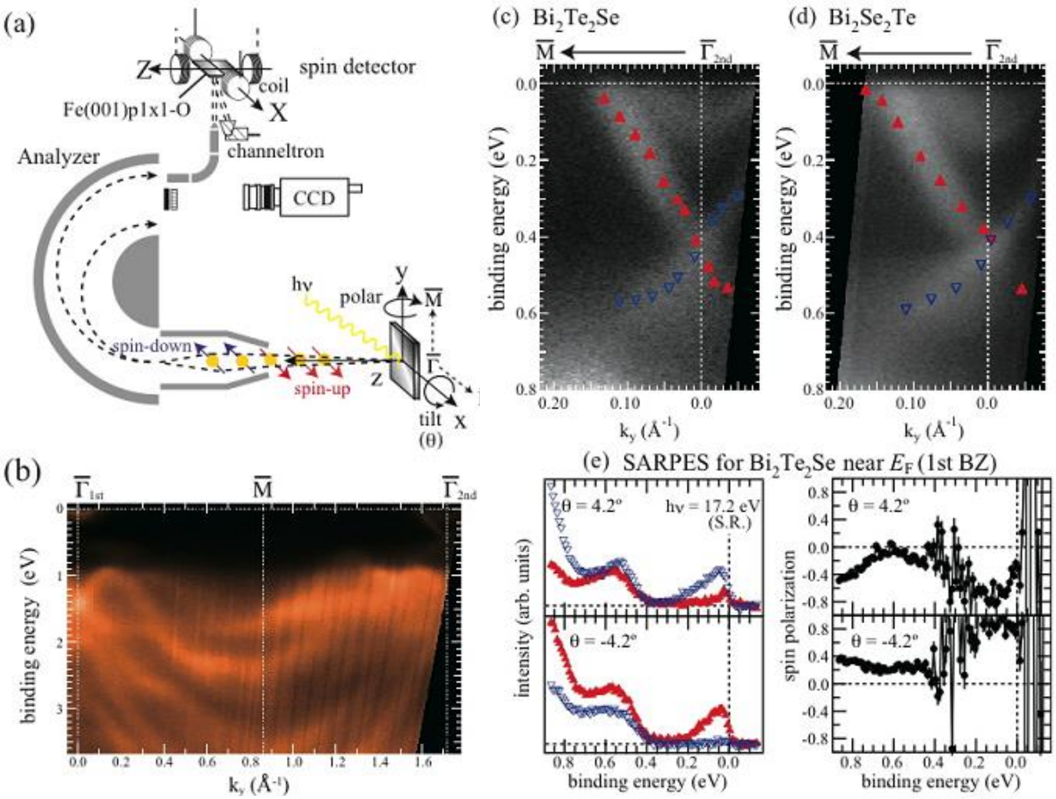


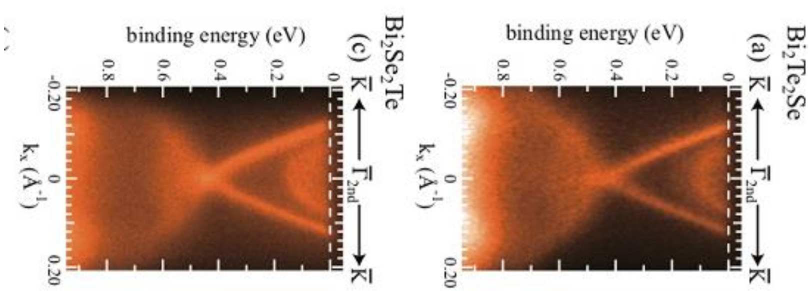
Magnetic monopoles

Topological Insulators

Rashba systems

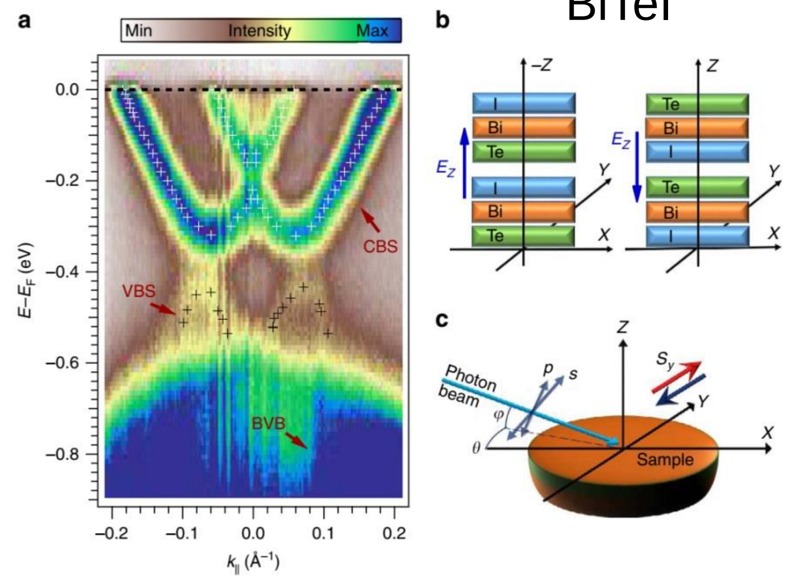
Spin-resolved ARPES (HiSOR, Hiroshima)





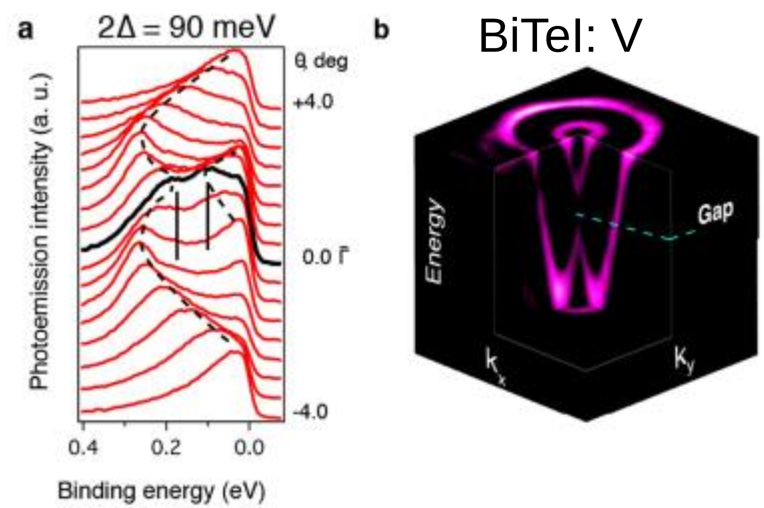
K. Miyamoto, et al. PRL (2012).

BiTeI



H. Maaβ, et al. Nature Comm. 7, 11621 (2016)

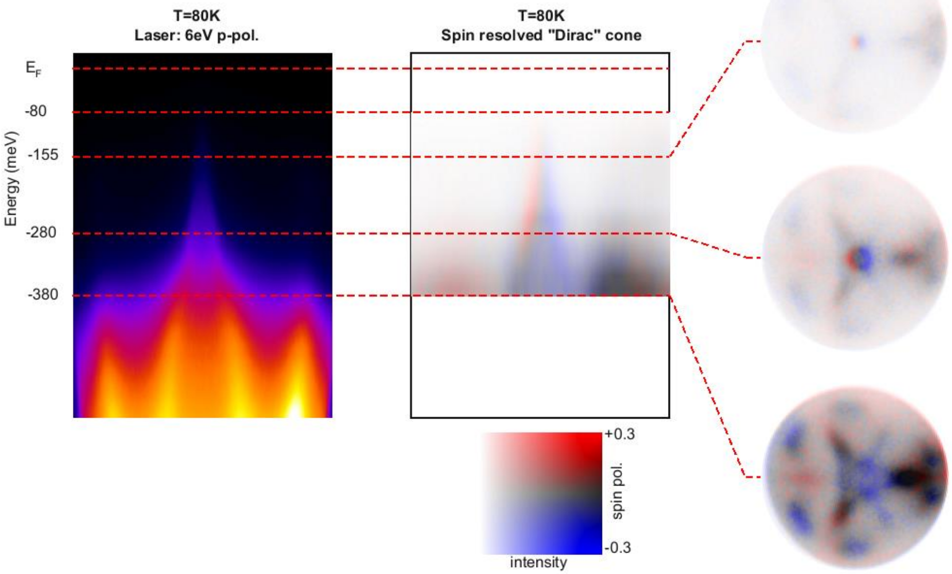
BiTeI: V

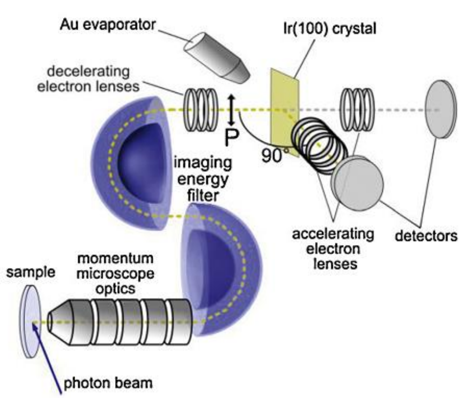


A.M. Shikin, et al. 2D Mater. 4 (2017) 025055

Crystalline Topological Insulator: PbSnTe case

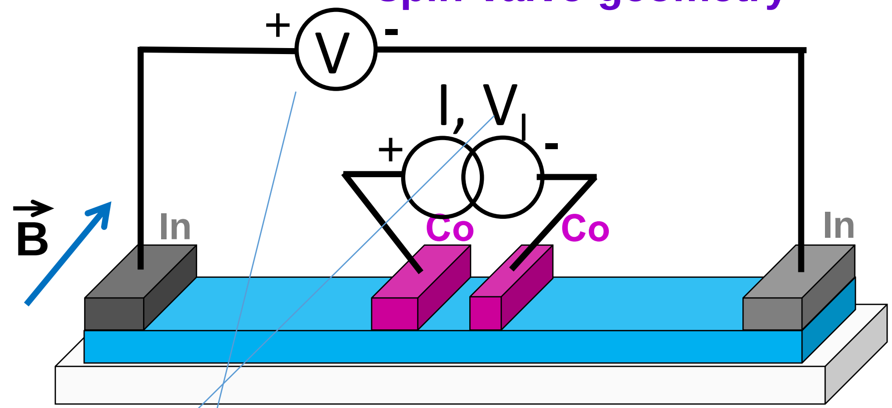
Photoelectron emission microscopy with an imaging spin filter

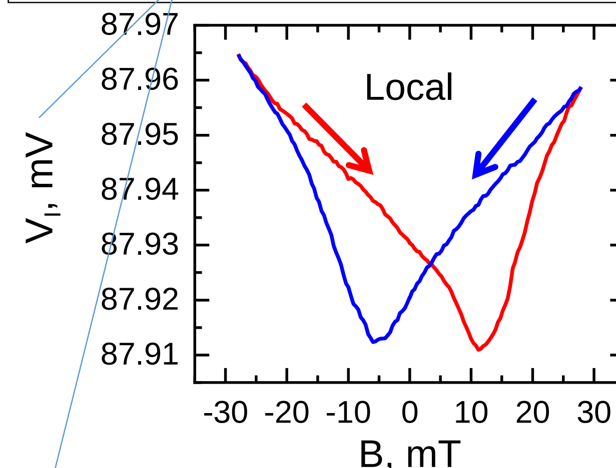


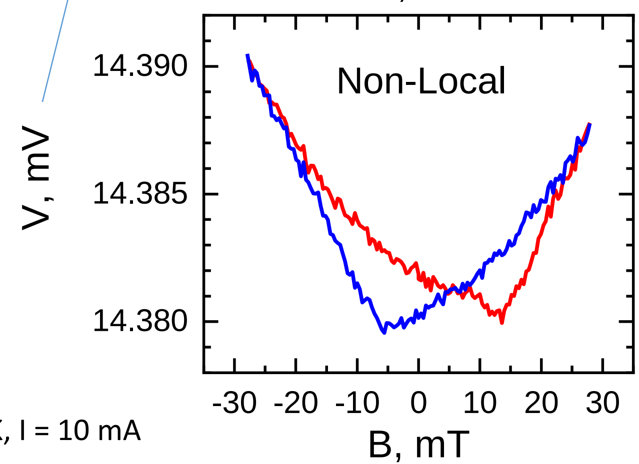


In collaboration with C. Tusche, Halle, 2014

Non-local signal in local spin-valve geometry

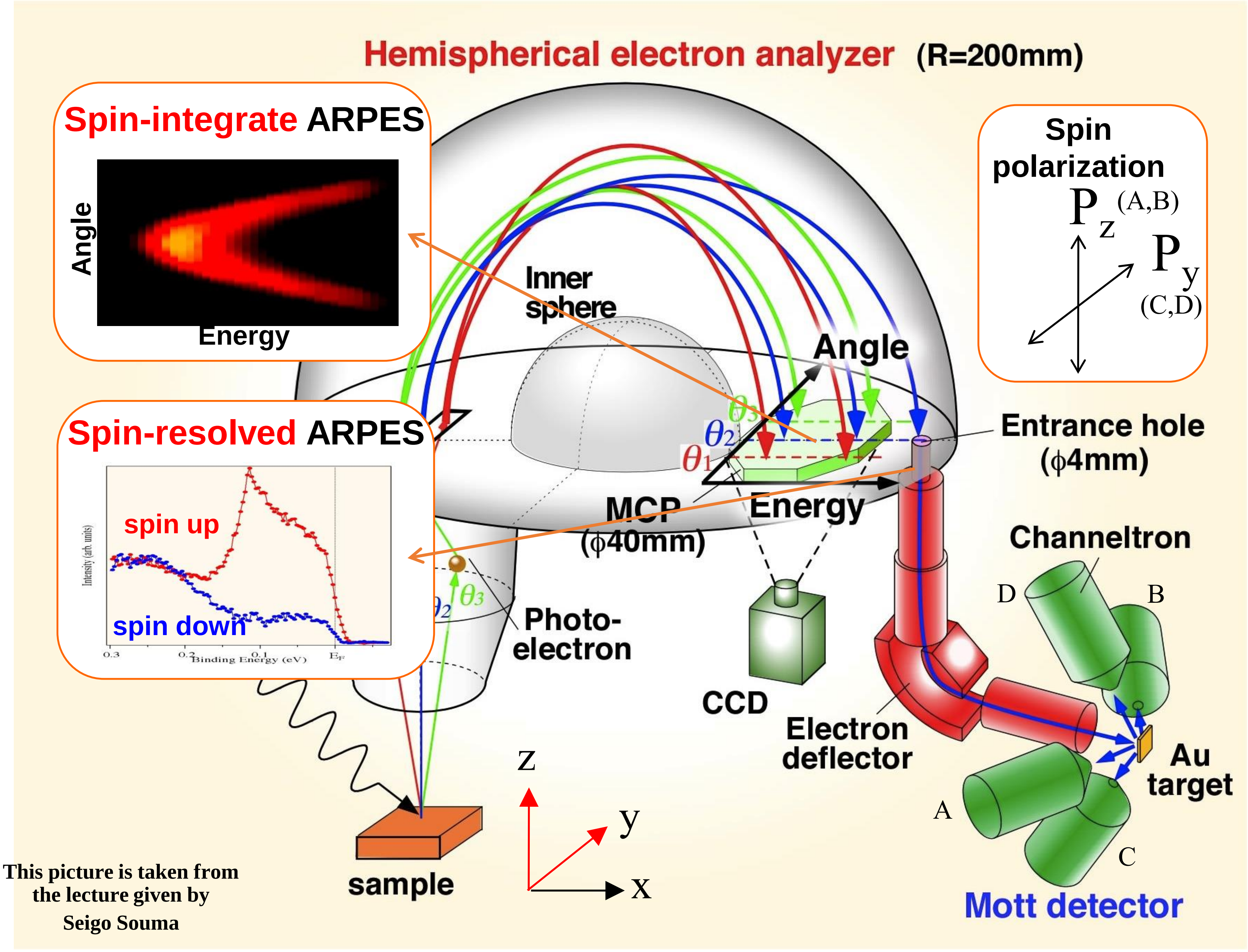






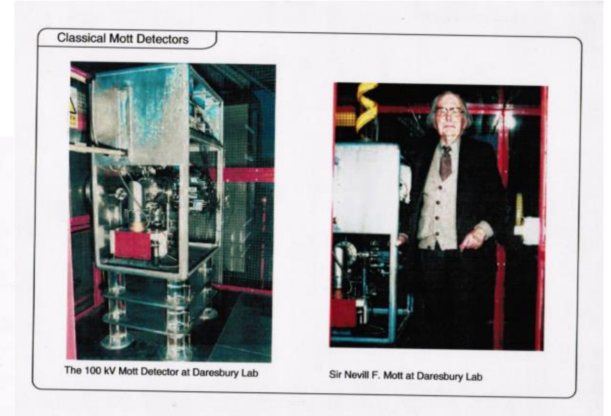
T = 4.2 K, I = 10 mA

Spin-resolved ARPES system



This picture is taken from the lecture given by Seigo Souma

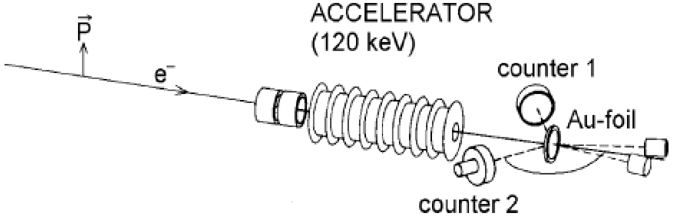
Spin detectors

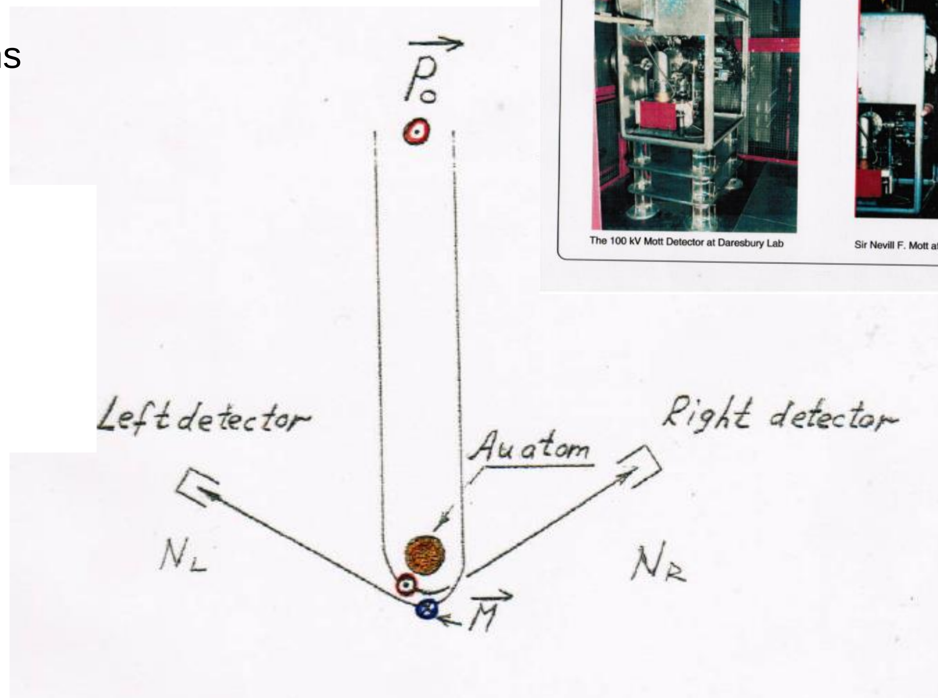


Mott detector

- based on the spin-orbit interaction of electrons

Schematic set-up of a Mott-detector





Best commercial spin detector features :

- Operating energy in the 10-150 keV range
- Selectivity close to **20 %** and **F ≈ $5 \cdot 10^{-5}$**
- Collection efficiency at best equal to **10^{-3}**
- Large volume (a few dm^3)

Table 1. A list of specifications of various spin polarimeters. $|S_{eff}|$ and I/I_0 are the effective Sherman function and the scattering probability, respectively. ϵ is the figure of merit or the efficiency of spin detection.

	Interaction	Energy	$\lvert S_{eff} \rvert$	I/I_0	ϵ
Conventional Mott [28]	Spin–orbit	100 keV	0.20	2.9×10^{-3}	1.1×10^{-4}
Compact Mott [29]–[31]		25–40 keV	0.14–0.15	9.7×10^{-3}	$1.9–5.6 \times 10^{-4}$
SPLEED [33]		150 eV	0.19	2.2×10^{-3}	8.0×10^{-5}
Diffuse scattering [34]		150 eV	0.19	9×10^{-3}	1×10^{-4}
VLEED (Fe surface) [35]	Spin-exchange	12 eV	0.4	0.1	2×10^{-2}
VLEED (O/Fe surface) [24]		6 eV	0.3–0.4	0.12	1.9×10^{-2}

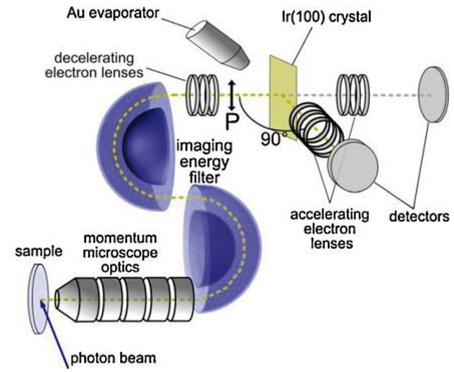
A. Nishide, et al. New J. of Physics, 12 (2010) 065011

Multichannel Spin-Polarization Detection

J. Kirschner, C. Tusche, et al. & G. Schönhense, et al.

D. Vasilyev et al. / Journal of Electron Spectroscopy and Related Phenomena 199 (2015) 10

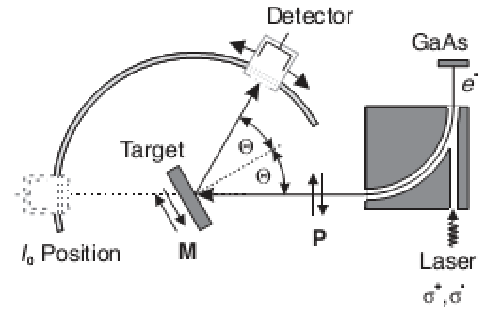
Low-energy electron reflection from Au-passivated Ir(001) for application in imaging spin-filters



Chr. Thiede, et al.

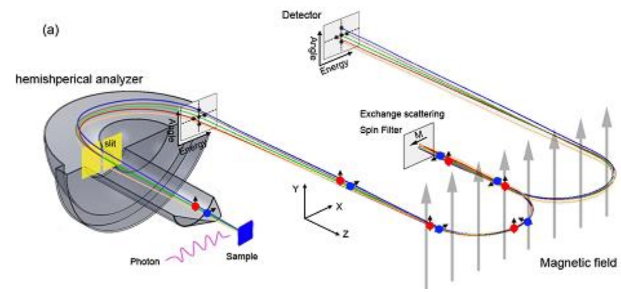
Display-Type Spin-Polarization Analyzer

PHYSICAL REVIEW APPLIED 1,054003 (2014)



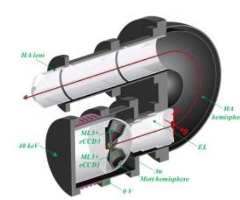
Fuhao Ji, et al. PRL 116, 177601 (2016)

Multichannel Exchange-Scattering Spin Polarimetry



V.N. Strocov, V.N. Petrov, et al.

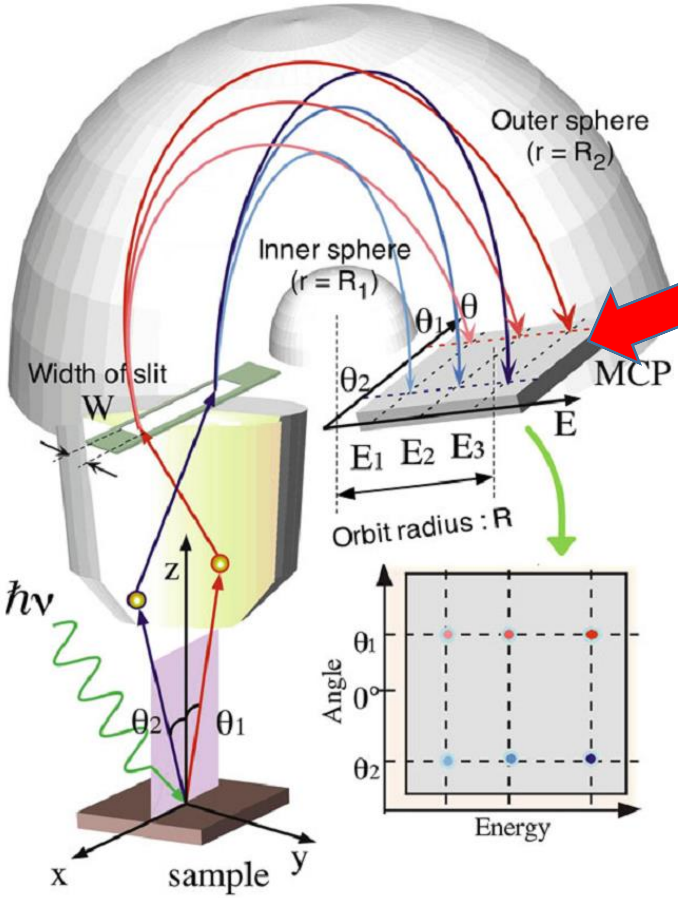
Concept of multichannel spin-resolving electron analyzer based on Mott scattering



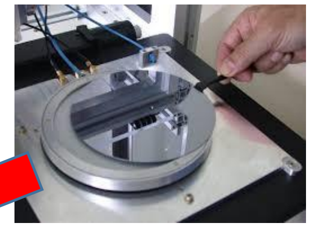
J. Synchrotron Rad. (2015). **22**, 708

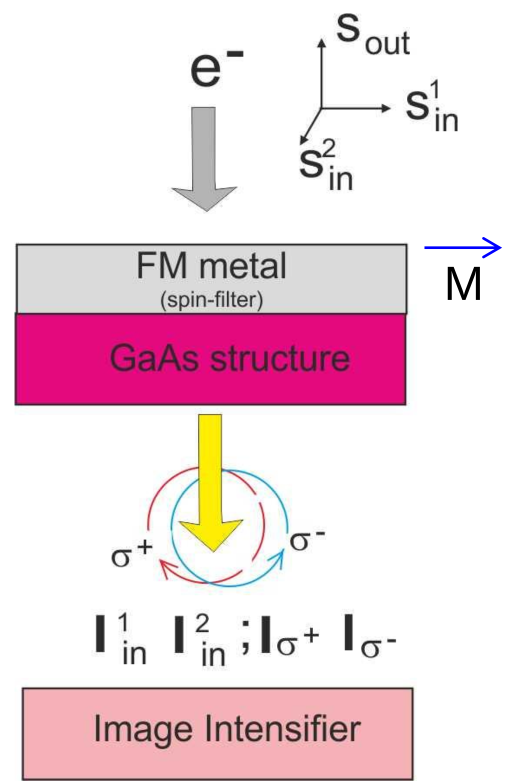
Motivation:

Concept of projection-type 3D spin-resolving electron analyzer based on Ferromagnetic - Semiconductor junction



FM/Semiconductor





The main idea:
Injection of electrons and
Detection of Cathodoluminescence.

JOURNAL OF SYNCHROTRON RADIATION

ISSN 1600-5775

A new imaging concept in spin polarimetry based on the spin-filter effect

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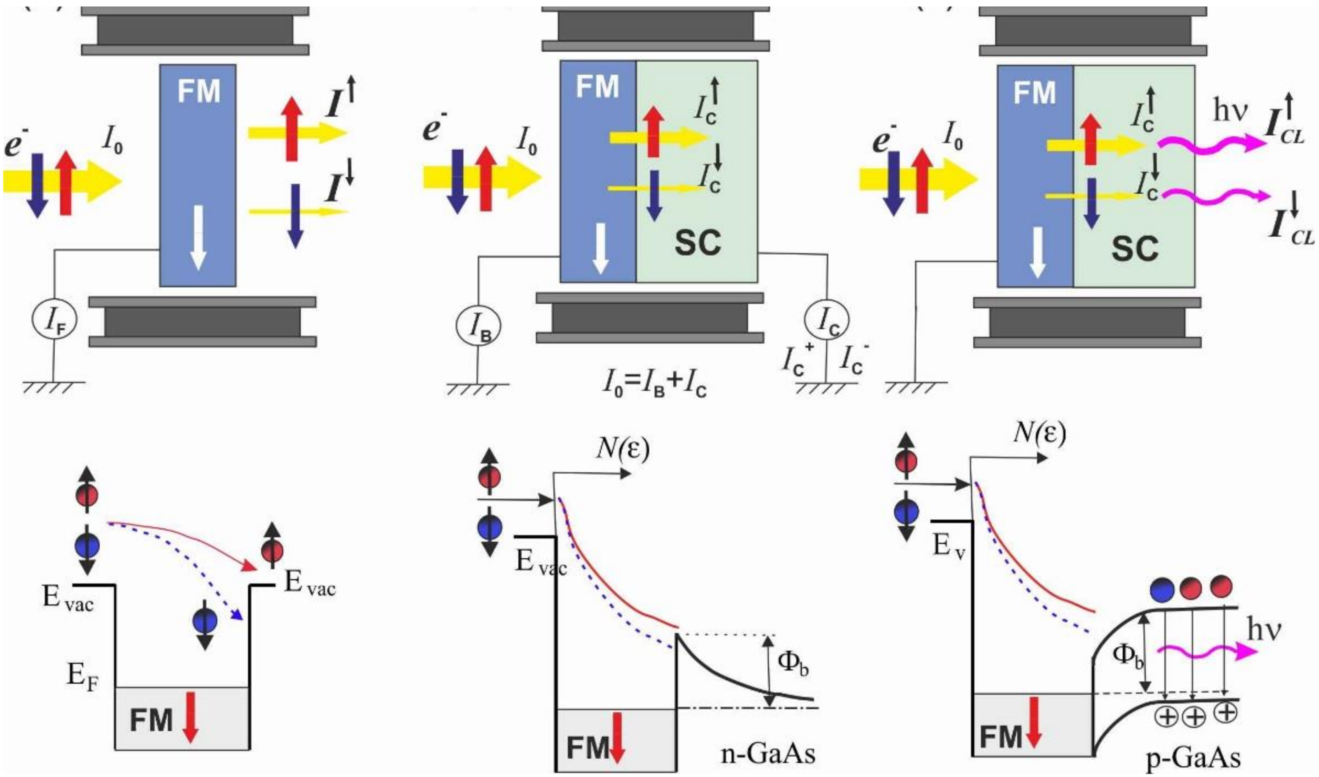
Received 7 November 2020
Accepted 28 February 2021



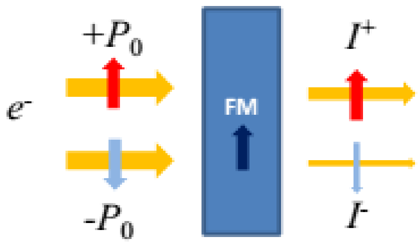
Filippe et al., 1998; Tereshchenko et al., 2011

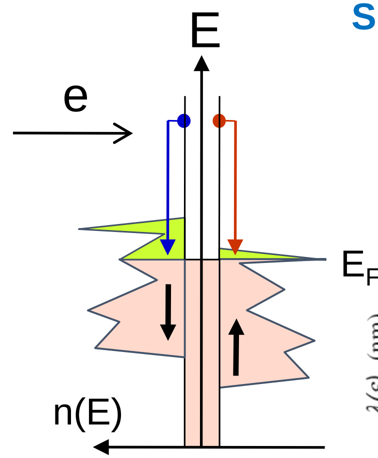
Schönhense & Siegmann, 1993;
Pappas et al., 1991;
Oberli et al., 1998;
Lassailly et al., 1994

X. Li, at al. Appl. Phys. Lett. 105, 052402 (2014).

Spin Filtering of Free Electrons by Magnetic Layers

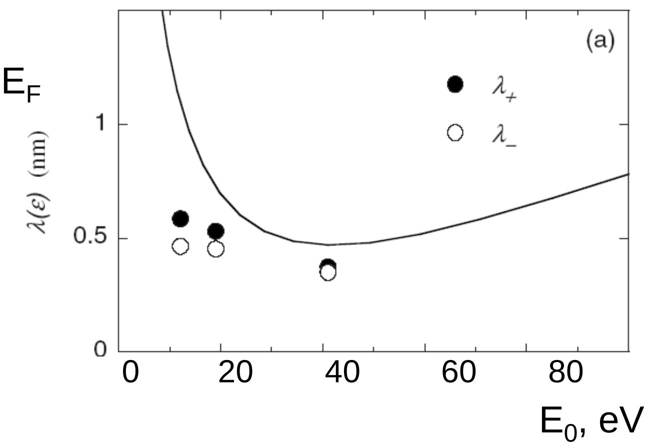
Idea of the spin-filter similar to an optical linear polarizer



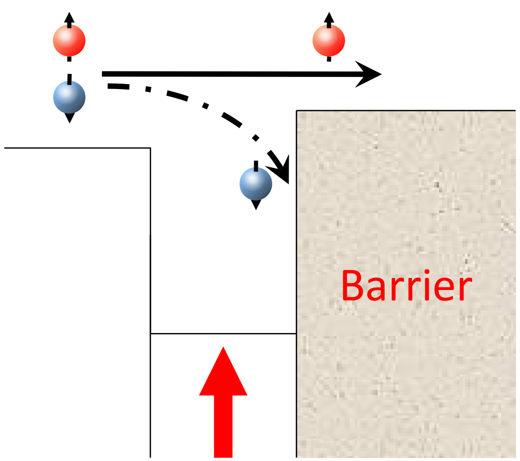


Spin-dependent mean free path

$$\frac{1}{\lambda_{\pm}(\varepsilon)} \approx \frac{1}{\lambda(\varepsilon)}\left[1 \mp \frac{\lambda(\varepsilon)}{\delta(\varepsilon)}\right]$$



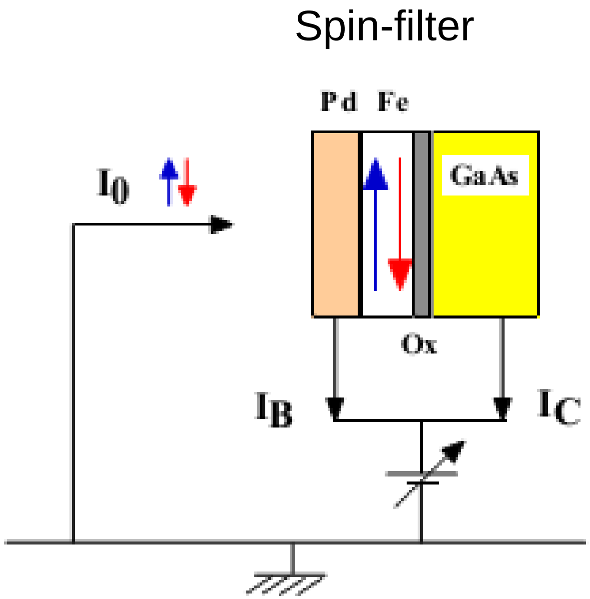
D.P. Pappas, et al. PRL 66 (1991) 504

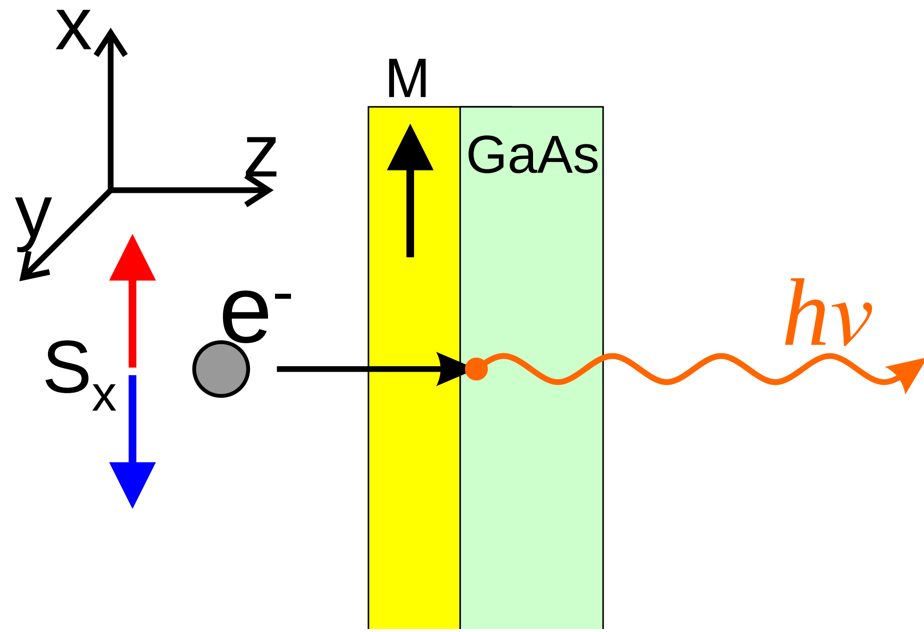


Spin selection → Energy barrier

→ Metal / Semiconductor junction

In plane polarization detection





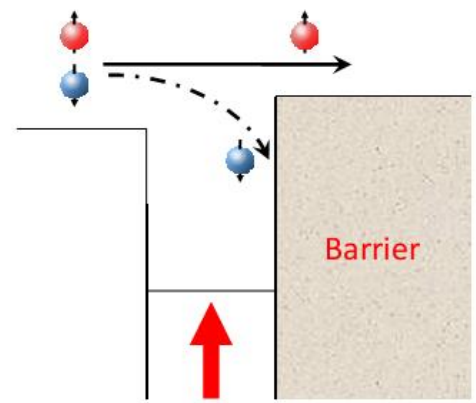
$$A = \frac{I_M^{+} - I_M^{-}}{I_M^{+} + I_M^{-}}$$

$$P_{in\ plane} = A/S$$

$$F = S^2 * I/I_0$$

Device characteristic:

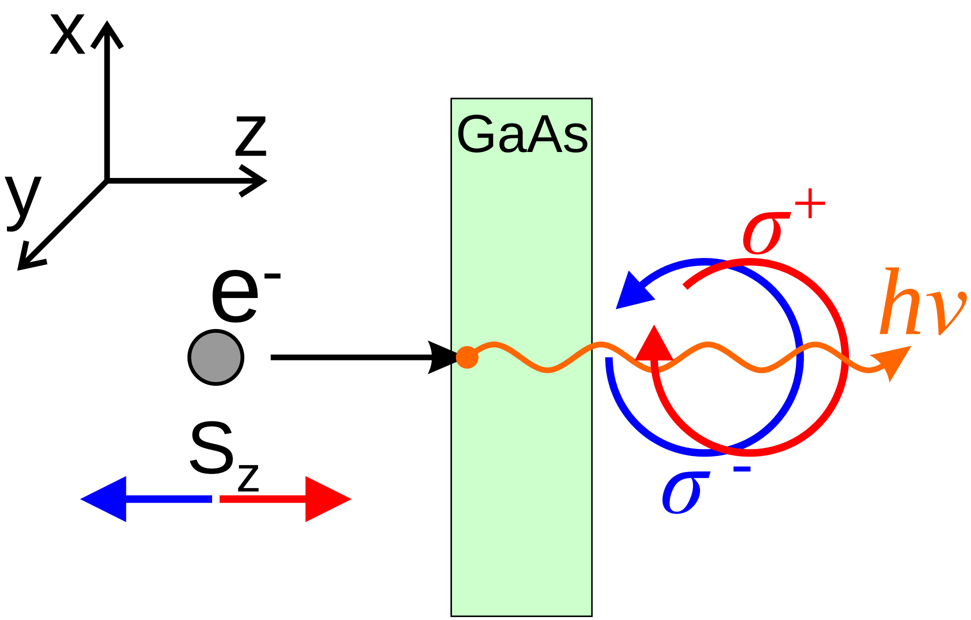
- $E^* \sim 700$ eV
- $F \approx 10^{-4}$
- compact



O. E. Tereshchenko, D. Lamine, G. Lampel, Y. Lassailly, X. Li, D. Paget, J. Peretti, J. of Appl. Phys. 109, 113708 (2011).

X. Li, O.E. Tereshchenko, S. Majee, G.Lampel, Y. Lassailly, D. Paget, J. Peretti, Appl. Phys. Lett. 105, 052402 (2014).

Measurement of out-of-plane spin polarization component



$$A = \frac{I\sigma^+ - I\sigma^-}{I\sigma^+ + I\sigma^-}$$

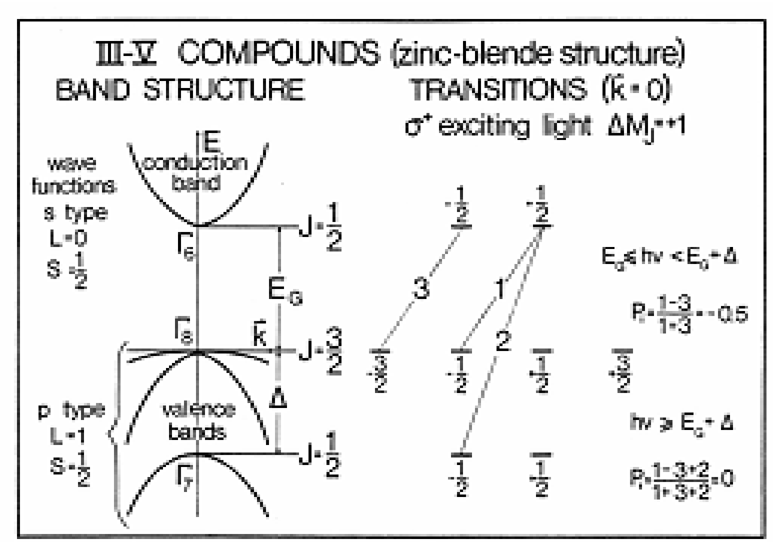
$$Pz = A/S$$

$$F = S^2 * I/I_0$$

GaAs:

Photoluminescence polarization:

$$P = \frac{P_0}{1+\tau/\tau_S} \sim 0{,}5\, P_0 \rightarrow \boxed{S = 0.5}$$



PL yield ~ 2% → $I/I_0 = 0.02$ (x10)

$F_1 = S^2 * I/I_0 = 0.5^2 * 0.02 \sim 5 \cdot 10^{-3}$

$F_m = N * F_1 = 10^6 * 5 \cdot 10^{-3} \sim 5000$

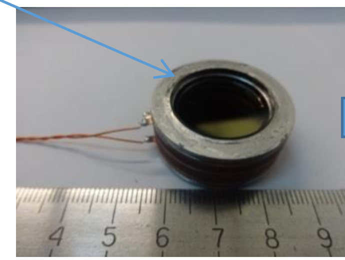
Image Intensifiers: 50 lines per mm, → 20x20 mm *50*50= 10^6 pixels

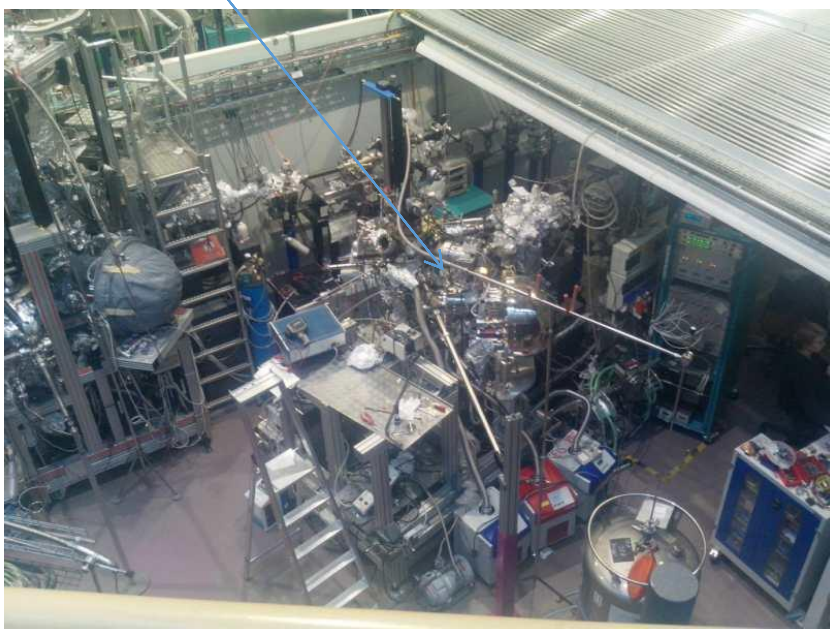
Analyzers aspect ratio

100:1

ARPES system

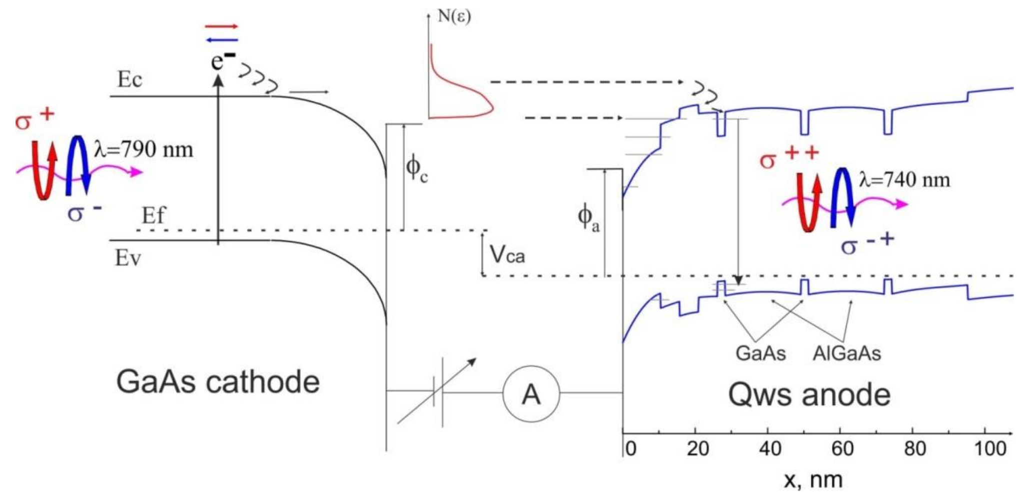
Vacuum photodiode



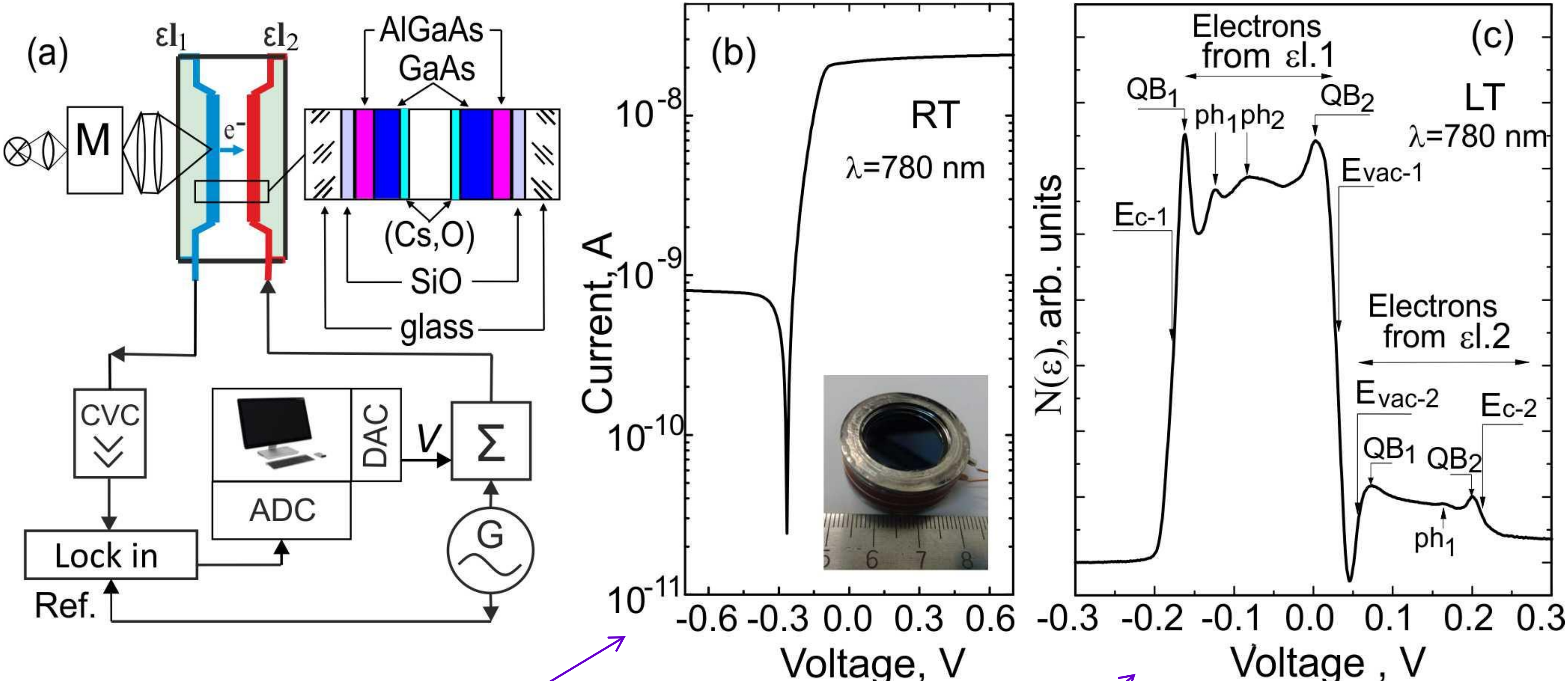


Advantages of two-side NEA vacuum photodiode:

- Photoemission physics of very low-energy electrons (0-300 meV)
- Source of spin-polarized electrons
- Injection physics of spin polarized electrons
- Spin-detector with spatial resolution



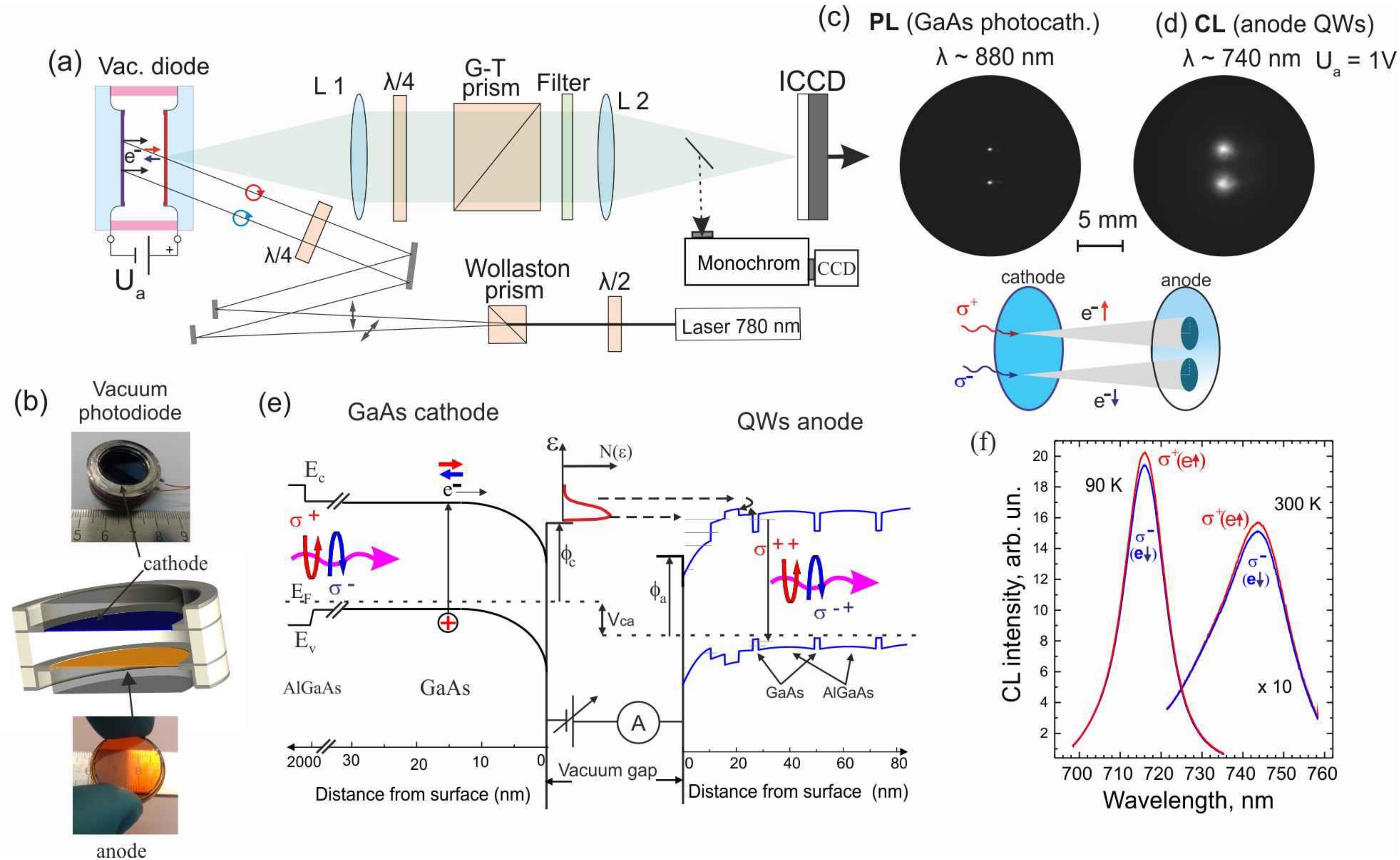
Measurement of Energy Distribution Curves of emitted electrons



$$J(V) = \int_0^\infty eN_{\varepsilon l1}(E)T_{el2}(E^*)dE - \int_0^\infty eN_{\varepsilon l2}(E)T_{\varepsilon l1}(E^*)dE$$

$$\frac{dJ}{dV} = \int_0^\infty eN_{\varepsilon l1}\frac{\partial T_{c2}(E^*)}{\partial V}dE - \int_0^\infty eN_{\varepsilon l2}\frac{\partial T_{c1}(E^*)}{\partial V}dE = N_1(E_\perp) - N_2(E_\perp)$$

Experimental realization of electron polarization spatial detection



Development of a semiconductor spin detector with spatial resolution

research papers

JOURNAL OF SYNCHROTRON RADIATION

ISSN 1600-5775

2021

A new imaging concept in spin polarimetry based on the spin-filter effect

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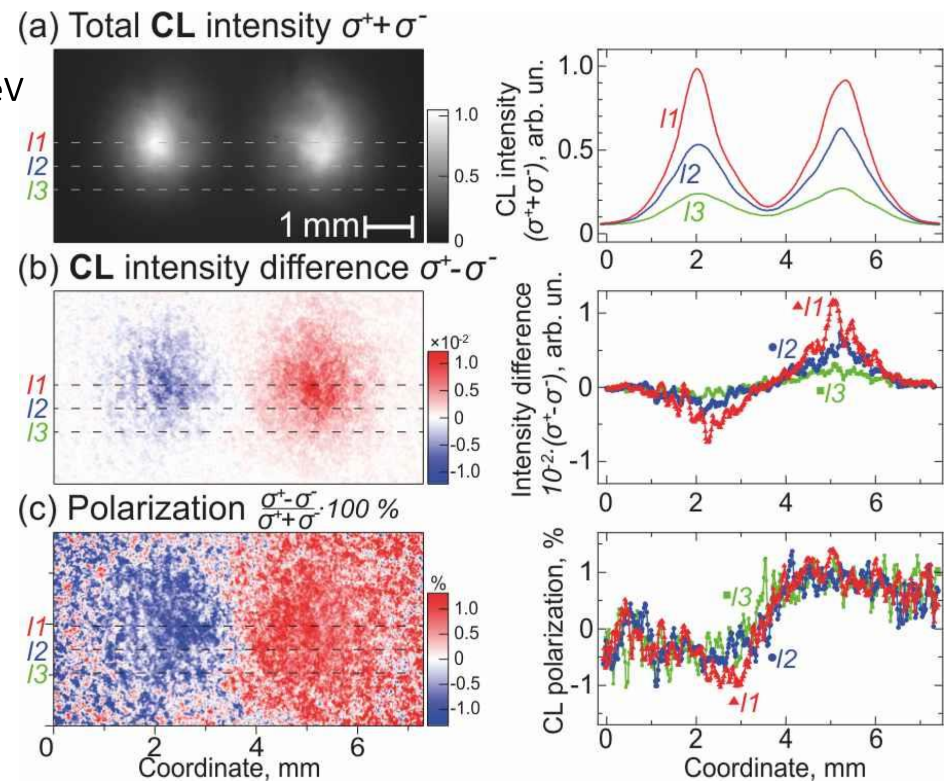
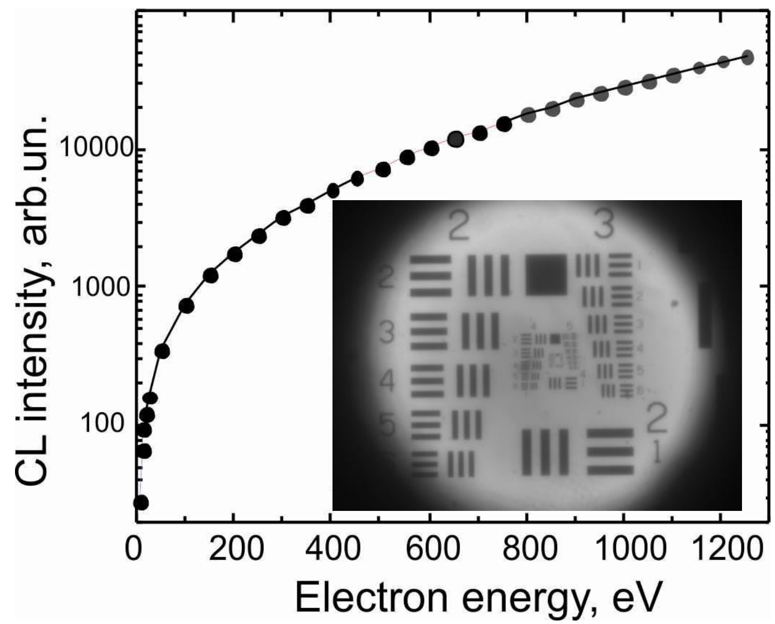
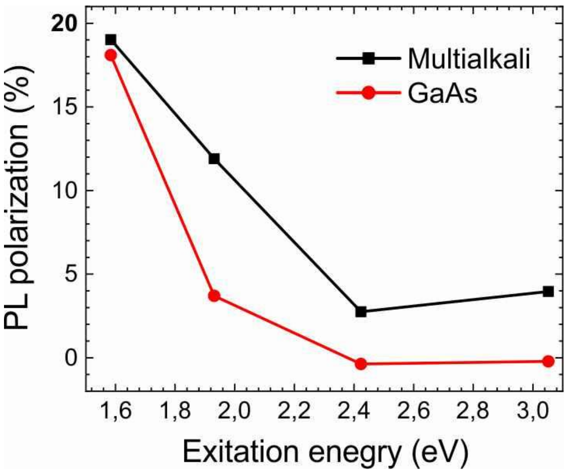
E_p=1 eV





New type of spin-polarized electron source based on multialkali photocathode

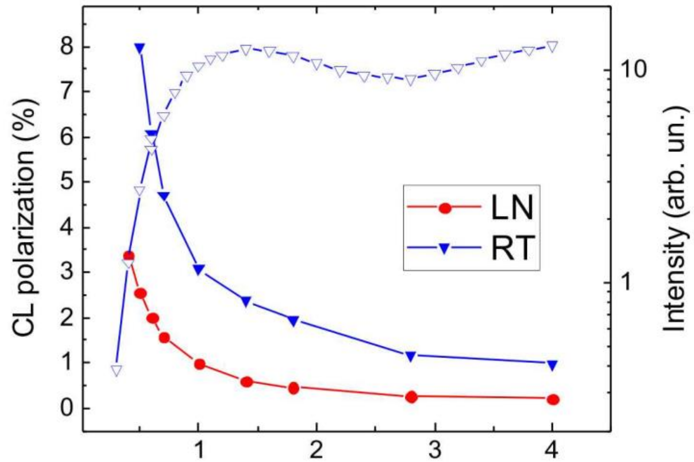
Polarized photoluminescence



Optical orientation of electron spins

Tablet-type photocathodes

Electron spin polarization

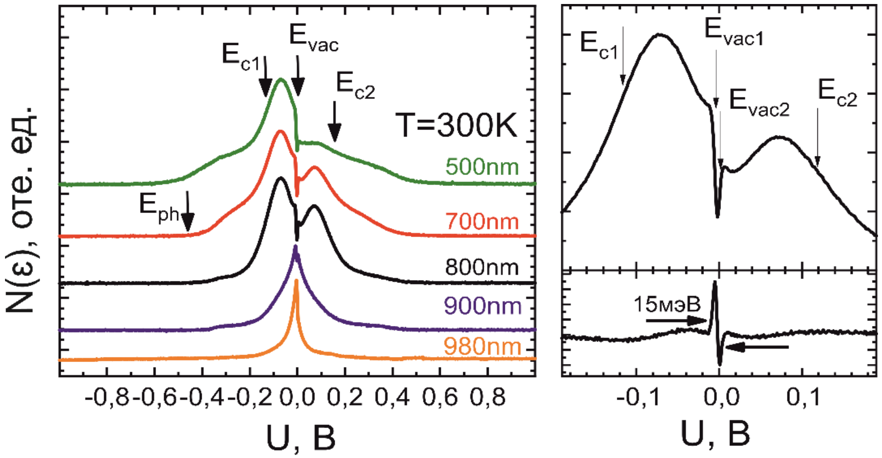


Electron Energy, eV

$P_0 \approx 50$ %

$E_{tr} \leq kT$

EDC

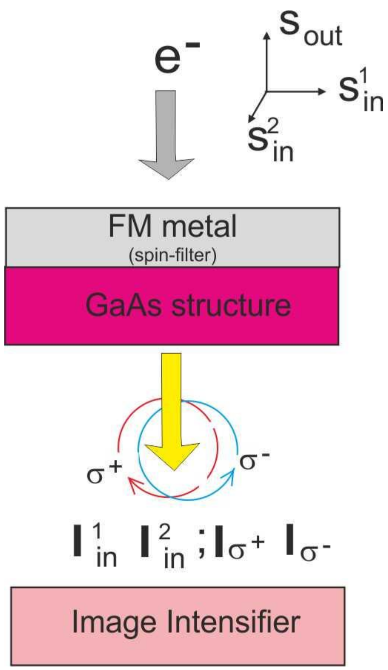


Summary

- **3D-type spin-detector with spatial resolution based on Ferromagnetic-Semiconductor junction is proposed.**

Detector characteristics:

- **Operation energy: 1-1000 eV**
- **Selectivity $S \sim 0.1$ (up to 0.5)**
- **Detection eff. $I/I_0 \sim 0.02$ (0.2)**
- **$F_1 = S^2 \times I/I_0 = 0.1^2 \times 0.02 \sim 10^{-4}$ (10^{-2})**
- **Number of channels: 10^6**
- **stable and compact**



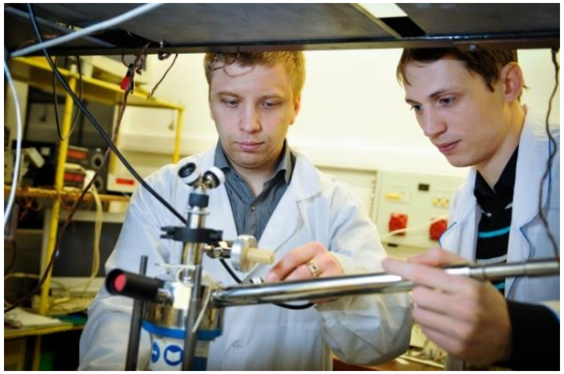
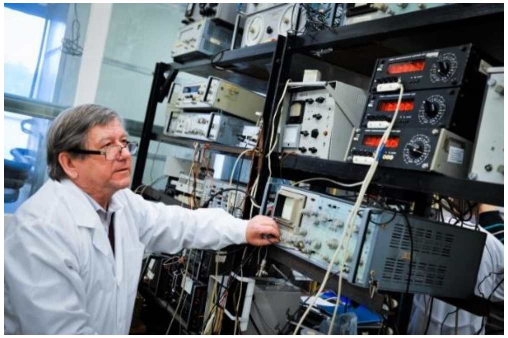
Сотрудники лаборатории физики и технологии гетероструктур ИФП СО РАН



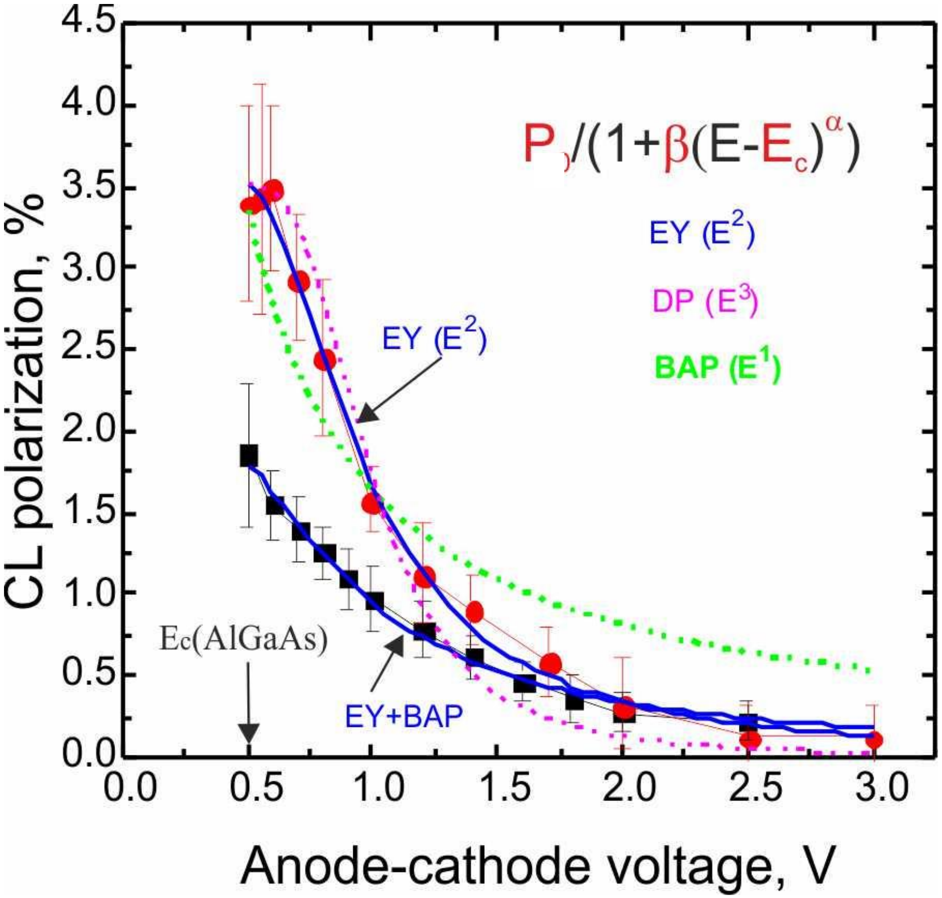







Detection of spin polarization by polarized cathodoluminescence depending on the electron energy



$P_{CL} = P_0 * k_1 * k_2 * k_3$

$P = \frac{P_0}{1+\tau/\tau_s}$

P_0=20%

$\mathbf{P_{CL} = P_0/[(1 + \tau_{QWr} / \tau_{QWs})(1 + \tau_r / \tau_s)]}$

$\tau_s(E) \sim E^{-\alpha}$

α = 3 Dyakonov-Perel

α = 2 Elliott Yafet

α = 1 Bir- Aronov-Pikus

$S=P_{CL}(E)/P_0 = 0.1/(1+2.3(E-0.48)^{1.5})$

A=S≈0.1 (Sherman function)

$F=S^2 I/I_0$ – Figure of merit

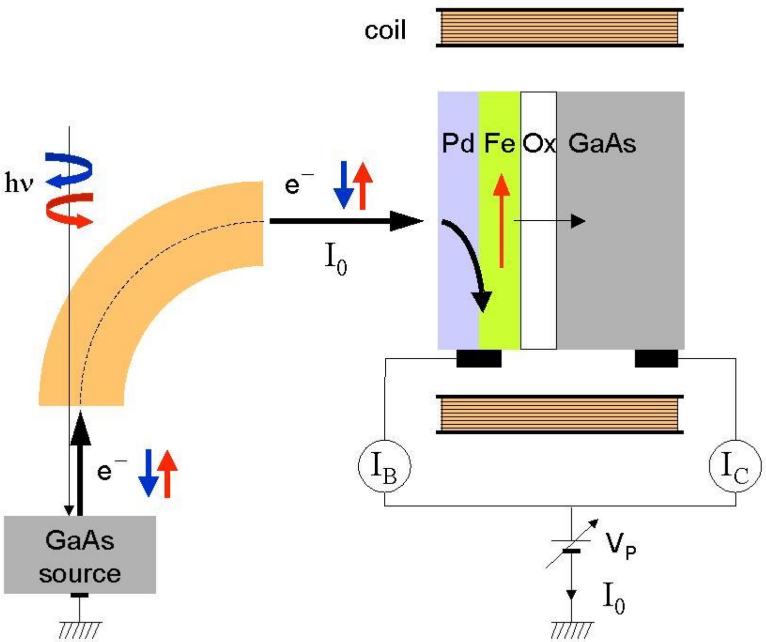
I/I_0~2% (PL)

$F=10^{-2}\, 4\times10^{-2} = 4\times10^{-4}$

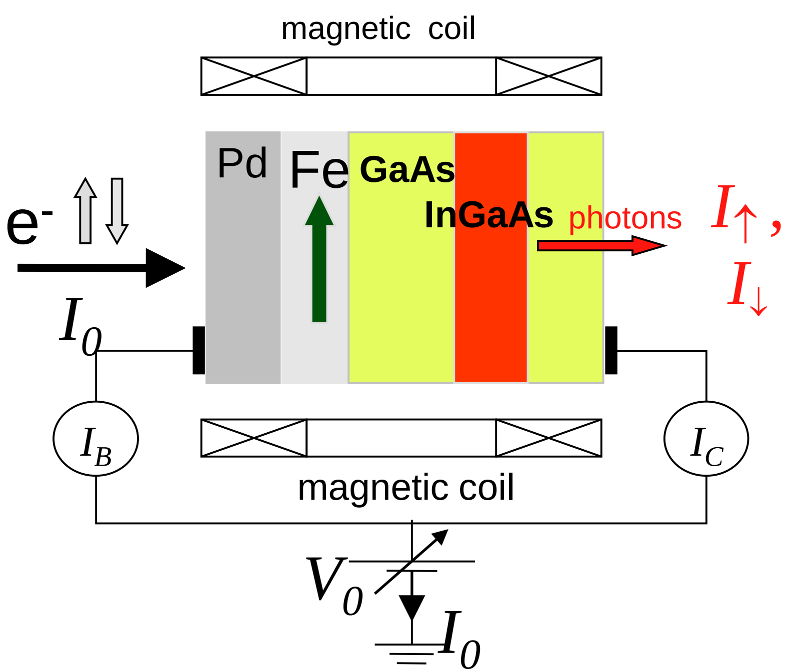
Spin-filtering effect: electrical vs optical registration

The principle: injection of spin-polarized electrons from vacuum into a ferromagnetic metal layer deposited on a semiconductor substrate and to measure the spin-dependent transmission through the Schottky junction.

Electrical registration



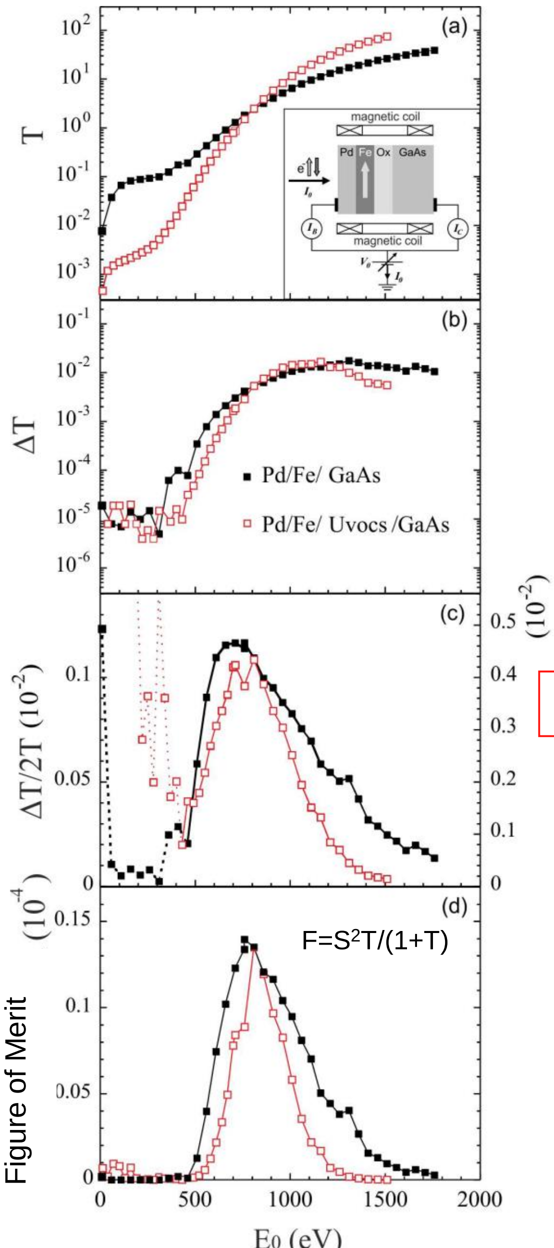
Optical registration



O. E. Tereshchenko, D. Lamine, G. Lampel, Y. Lassailly, X. Li, D. Paget, J. Peretti, **J. of Appl. Phys. 109, 113708 (2011).**

X. Li, O.E. Tereshchenko, S. Majee, G.Lampel, Y. Lassailly, D. Paget, J. Peretti, **Appl. Phys. Lett. 105, 052402 (2014).**

Electrical registration of spin-polarized electrons in magnetic Schottky barriers



$T = I_c/I_0$ – transmission function

$\Delta T = (I_c^{+} - I_c^{-})/I_0 = \Delta I_c/I_0$ – spin-dependent transmission function

$A_c = (I_c^{+} - I_c^{-})/(I_c^{+} + I_c^{-}) = \Delta T/2T$ – spin-dependent asymmetry

$S = A_c/P_0$ – Sherman function

$P = A_c/S$ – polarization

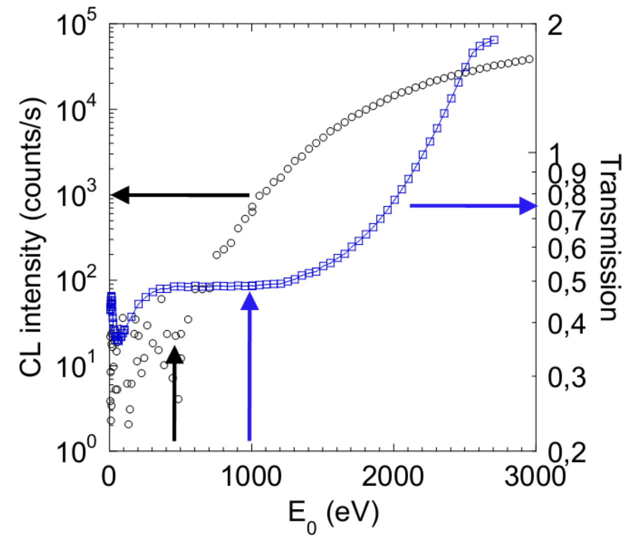
Device characteristic:

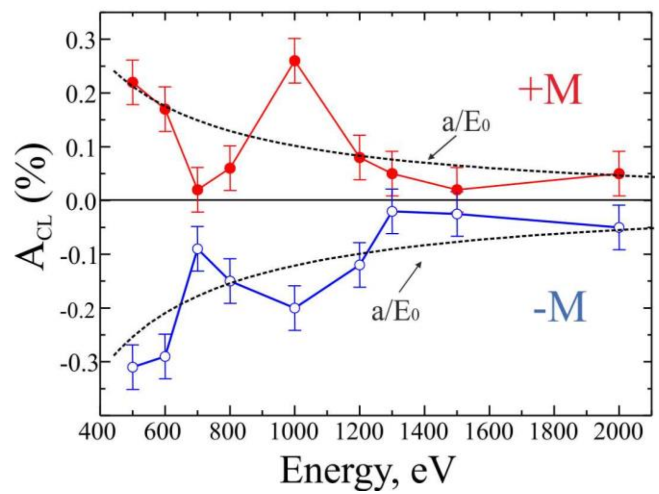
- **optimal Energy**

E^{*} ~ 700 eV

- **Selectivity S ~ 0.2-1 %**
- **Detection eff. ~ 1**
- **F ≈ (2-10)·10^{-5}**
- **compact** JAP (2012)

Optical registration of spin-polarized electrons in Pd/Fe/GaAs/InGaAs(001)





X. Li, O.E. Tereshchenko, S. Majee, G.Lampel, Y. Lassailly, D. Paget, J. Peretti, Appl. Phys. Lett. 105, 052402 (2014).

Motivation: ***the least emittance is the most advanced ARPES !***

The 1^4 ARPES station at SKIF: 1meV *1 meV*1 K*1 μm

beam spot size ≤ 1 μm

+ Imaging type spin detector

BESSY example:

The One-Cube ARPES 1^3 station at BESSY: the excitation source and the electron energy analyzer as well as the sample temperature – have been reduced to ≤1 meV:

1meV *1 meV*1 K

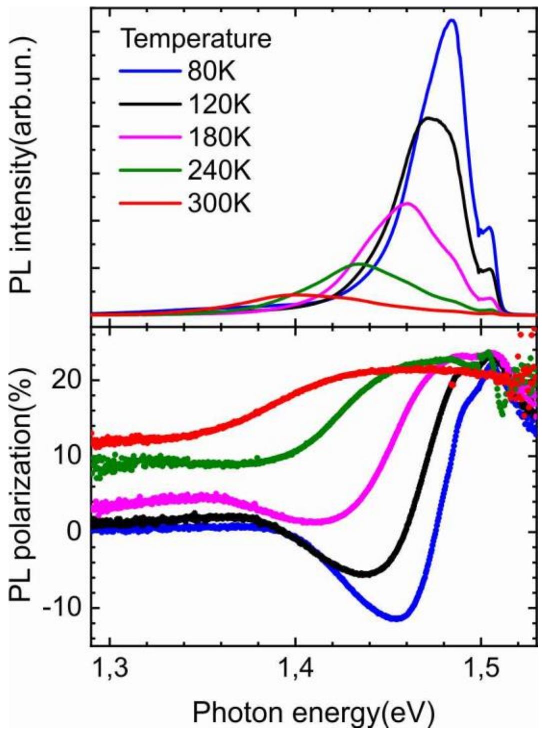
SPECS™

SKIF ARPES Endstation Requirement Analysis

Only proven solutions considered!

requirements Inst SemiCon Physics	KREIOS (MM) System	ASTRAIOS System	ASTRAIOS w HESTIA
Small Spot Capability (<1μm stability)	+ (Fully met)	− (Not met)	+ (Fully met)
Ultra Low Temperature Analysis (T<4K)	− (Not met)	+ (Close to be met)	− (Not met)
Spin Detector Support (incl. homebuilt designs)	+ (Fully met)	+ (Fully met)	+ (Fully met)
ARXPES/XPD	+ (Close to be met)	+ (Fully met)	− (Not met)
Ultra high energy Resolution analyzer (ΔE<1meV)	− (Not met)	+ (Close to be met)	+ (Close to be met)

+ Fully met   + Close to be met   − Not met


PL intensity(arb.un.)
Temperature
80K
120K
180K
240K
300K
PL polarization(%)
20
10
0
-10
1,3
1,4
1,5
Photon energy(eV)

Terahertz-induced Dirac fermions acceleration

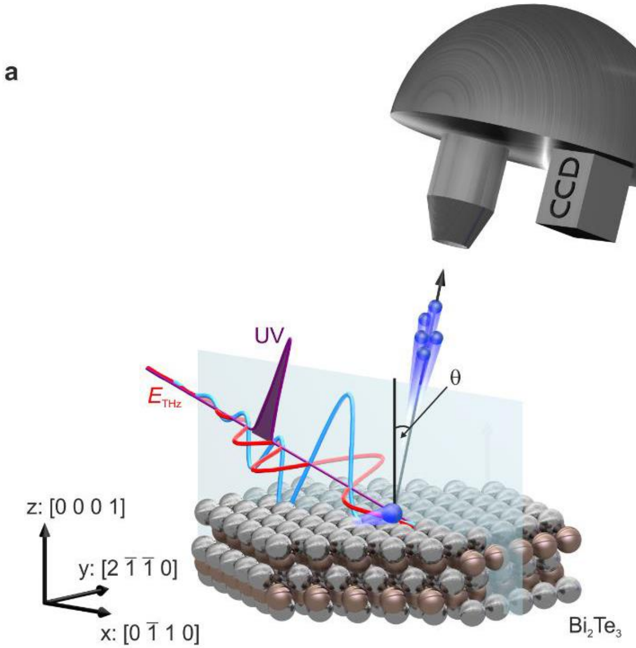
LETTER

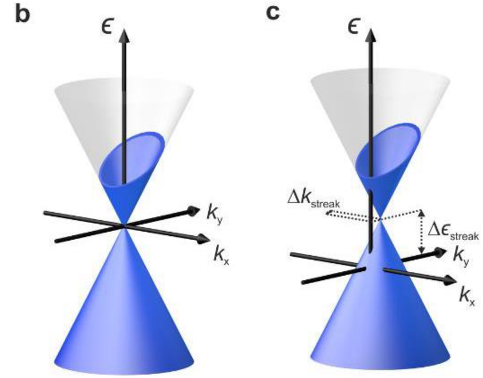
Nature, 2018

https://doi.org/10.1038/s41586-018-0544-x

Subcycle observation of lightwave-driven Dirac currents in a topological surface band

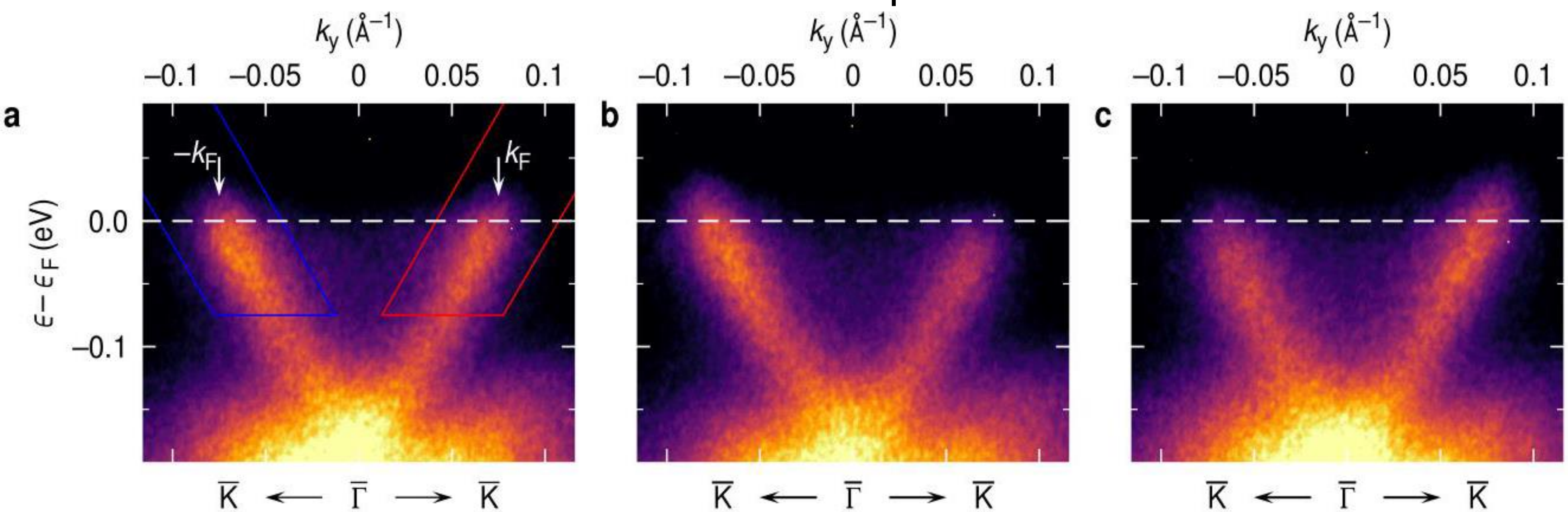
J. Reimann[1], S. Schlauderer[2], C. P. Schmid[2], F. Langer[2], S. Baierl[2], K. A. Kokh[3,4], O. E. Tereshchenko[4,5], A. Kimura[6], C. Lange[2], J. Güdde[1], U. Höfer[1]* & R. Huber[2]*



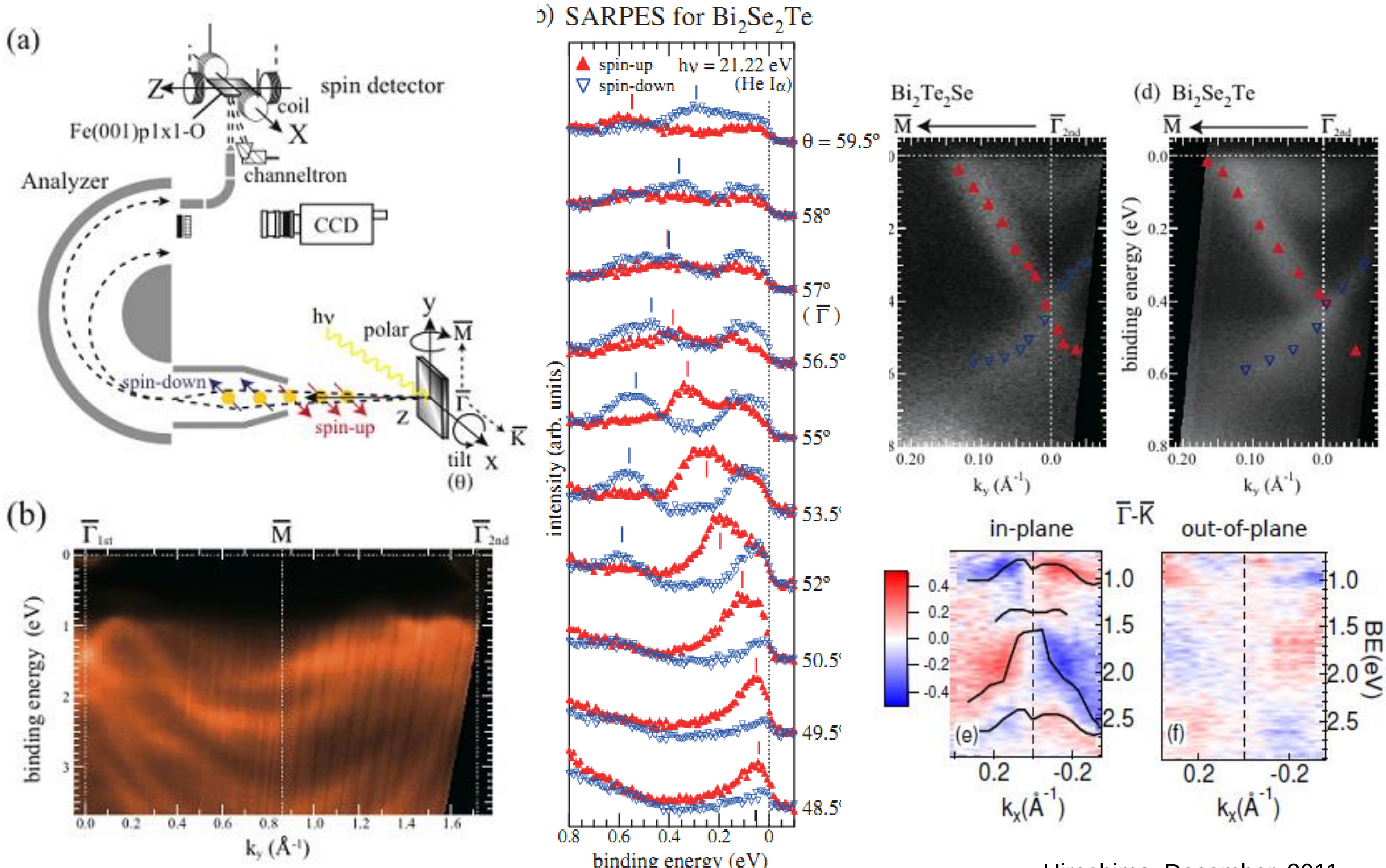


t = 0.1 ps

t = 0.6 ps



Spin-resolved ARPES: Topological Insulator study



Hiroshima, December, 2011

K. Miyamoto, A. Kimura, T. Okuda, H. Miyahara, K. Kuroda, H. Namatame, M. Taniguchi, S. V. Eremeev, T. V. Menshchikova, E. V. Chulkov, K. A. Kokh, O. E. Tereshchenko, Phys. Rev. Lett. (2012).

ARPES light sources (6-200 eV)

Type	Available photon energies	Bandwidth/monochromaticity	Intensity	Polarization
Laser	6-11 eV; not much variation for a given laser	Can be <<1 meV	Potentially high	Variable polarization
Gas (He, Xe, Ne, Ar…) discharge lamp	21.2, 40.8, 8.4, 9.6, 11.6 eV (and more)	Can be small (<1 meV) with monochromator	Sometimes low	unpolarized
Synchrotron	Variable; different synchrotrons and endstations specialize in different energy ranges	0.5 to several meV; tradeoff between bandwidth and intensity	tradeoff between bandwidth and intensity	Several fixed polarizations

$$E_{kin} = h\nu - \phi - |E_B|$$

$$\mathbf{p}_{\parallel} = \hbar \mathbf{k}_{\parallel} = \sqrt{2mE_{kin}} \cdot \sin\vartheta$$

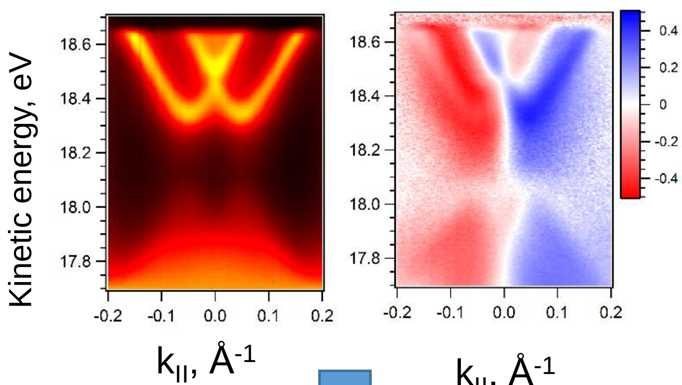
$$M^{\boldsymbol{k}}_{f,i} \equiv < \phi^{\boldsymbol{k}}_f | -\frac{e}{mc}\boldsymbol{A}\cdot\boldsymbol{p}|\phi^{\boldsymbol{k}}_i >$$

I. Формирование комбинированной электронной структуры спин-поляризованных поверхностных состояний Дирака и Рашбы

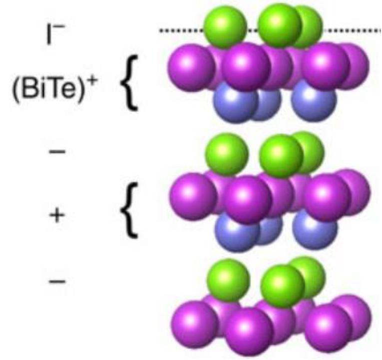
BiTeI -полупроводник (Eg=0.7 эВ) с гигантским расщеплением Рашбы

Spin-Polarized ARPES

Spin-polarized valance band spectra of initial surface

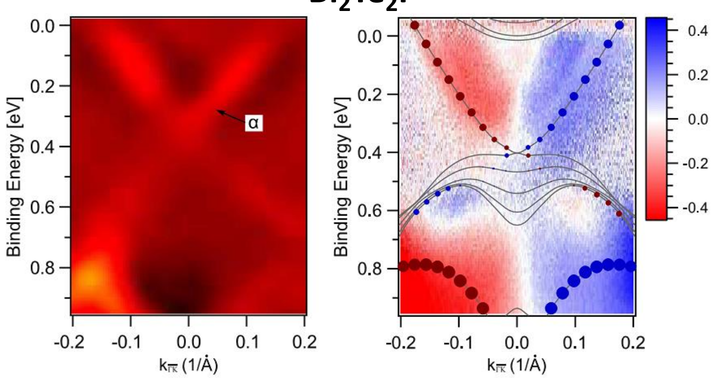


BiTeI Structure

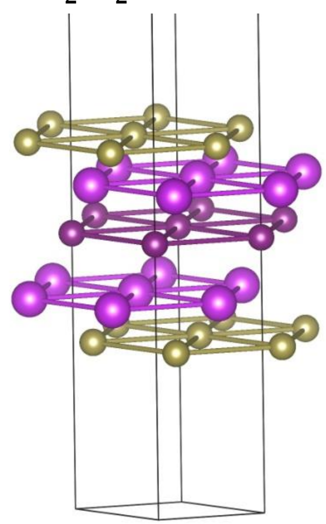


Annealing up to 230°C

Spin-polarized valance band spectra Bi_2Te_2I

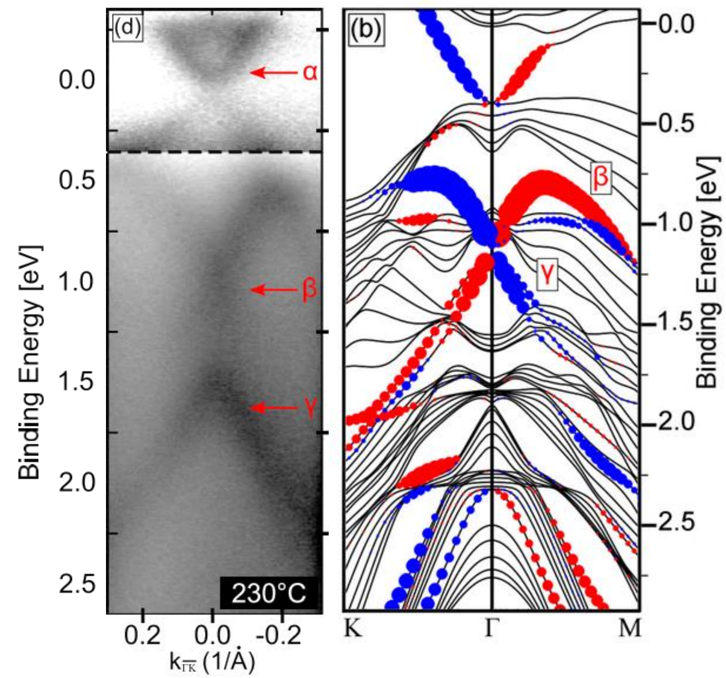


Bi_2Te_2I Structure



BESSY II

Valence band spectra after heating up to 230 C



Nature Communications, 2016, v. 7, p. 11621.

S. Fiedler et al. New J. Phys. 20 (2018) 063035