Fizyka przyrządów spintronicznych z nanodrutów półprzewodnikowych

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Wykład wygłoszony na konferencji "From Spins to Cooper Pairs",
Zakopane, 22-26 września 2014

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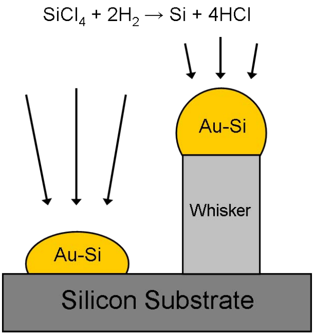
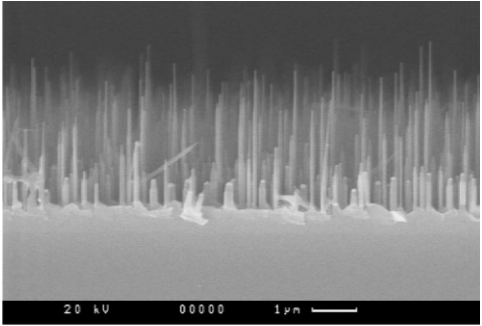
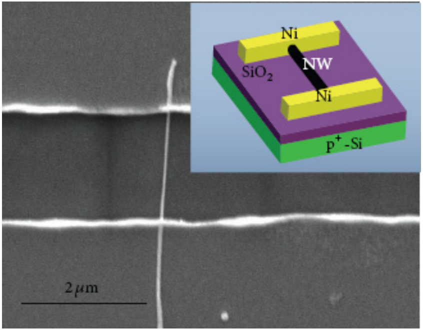


Vapor-liquid-solid (VLS) growth mechanism of Si semiconductor nanowire.

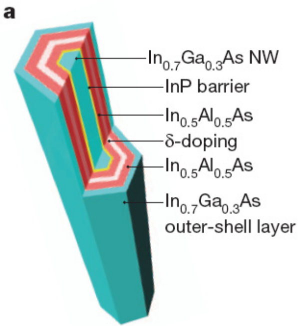


”Forest” of GaAs nanowires.



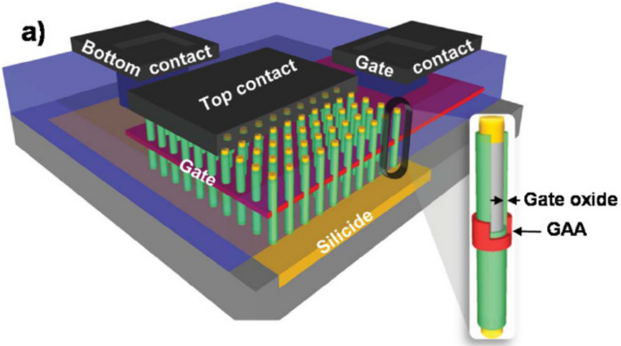
SEM image and (inset) schematic of a back-gated InSb nanowire field-effect transistor with Ni metal contacts.

M. Fang et al., J. Nanomaterials (2014).



Cross section of the hexagonal InGaAs core-shell nanowire.

K. Tomioka et al., Nature 488 (2012) 189.



Transistor based on *p*-type Si Gate-All-Around (GAA) nanowires.

G. Larrieu and X.-L. Han, Nanoscale 5 (2013) 2437.

Typical size of semiconductor nanowires:

length $L \sim 1\mu$m
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II. Spin filter
III. Spin transistor
IV. Summary

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This interaction is of relativistic origin and can be derived from either the classical electrodynamics or quantum relativistic theory (Dirac equation).

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These considerations can also be applied to the **holes** in semiconductors if – in the following formulas – we replace the electron charge $q = -e$, band mass m_e, etc., by the corresponding quantities characterizing the hole, i.e., $q = +e$, m_h, etc.

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Classical electrodynamics

If the electron with charge $q = -e$ (e is the elementary charge) and rest mass m_{e0} moves with velocity $\mathbf{v}$ in external magnetic ($\mathbf{B}$) and electric ($\mathbf{F}$) fields (measured in the laboratory frame), then – in the reference frame moving together with the electron – the electron experiences the magnetic field

$$\mathbf{B}_{eff} = \mathbf{B} + \mathbf{B}_{SO} \ , \tag{1}$$

where

$$\mathbf{B}_{SO} = -\frac{1}{c^2}\mathbf{v} \times \mathbf{F} \ . \tag{2}$$

Eq. (2) results from the Lorentz transformation of the electromagnetic field and is valid with the accuracy of $(v/c)^2$, where c = velocity of light in vacuum.

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The electron with spin **s** possesses the spin magnetic moment

$$\boldsymbol{\mu}_s = -\frac{g\mu_B}{\hbar}\mathbf{s} \,. \tag{3}$$

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Electron interacts with magnetic field B$_{eff}$ via the dipol-field interaction.

The energy of this interaction is given by

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$$E_Z = -\mu_s \cdot \mathbf{B} \tag{5}$$

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If the electric field is **central**, i.e., $\mathbf{F}(\mathbf{r}) = F_r(r)(\mathbf{r}/r)$, then Eq. (7) transforms into

$$E_{SO} = -\frac{e\hbar F_r}{2m_{e0}^2 c^2 r}\mathbf{s}\cdot\mathbf{l}\,, \tag{8}$$

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Relativistic quantum mechanics

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Spin interactions in semiconductors

The conduction-band electron in a semiconductor is described within the effective mass approximation (EMA). According to the EMA we make the following replacements:

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In semiconductors, $g^\star$ takes on different values: $g^\star > 2$, $g^\star < 2$, and even $g^\star < 0$.

E.g., for GaAs: $g^\star = -0.44$, while for magnetic semiconductors, e.g., CdMnTe, $g^\star$ can reach $\simeq 500$,

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The spin-orbit (SO) coupling in semiconductor can be obtained from Eq. (7) if we replace

electron-positron creation energy $\Longrightarrow$ electron-hole creation energy (semiconductor energy gap)

$2m_{e0}c^2 \simeq 1$ MeV $\Longrightarrow E_g \simeq 1$ eV

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$$H_{SO,R} = e\alpha\hat{\boldsymbol{\sigma}} \cdot (\mathbf{F} \times \hat{\mathbf{k}}) \;, \tag{9}$$

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The electrons in solids also experience the **internal** electric field generated by the atomic cores. This field also leads to the SO interaction (called the **Dresselhaus** interaction). This interaction depends on crystal structure, size of the nanostructure, and doping, but is independent of the external electric field $\mathbf{F}$.

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Model of nanowire

We assume that the electron motion is quasi-free in the growth direction (z) and confined in the transverse (x, y) directions.
The transverse confinement potential can be taken in the form of deep potential well. For the infinitely deep potential well we get the transverse energy levels

$$E_{n_\perp} = \frac{\hbar^2 \pi^2}{m_e} \left(\frac{n_\perp}{D} \right)^2 , \tag{10}$$

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In numerical calculations, the transverse potential well can be taken finite, but sufficiently deep.

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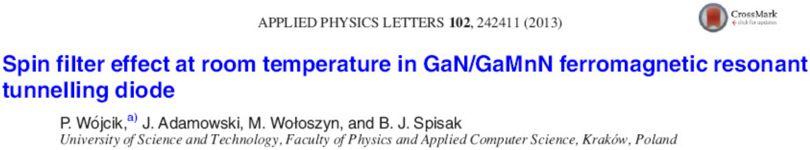
II. Spin filter

Results for mesa-type (planar) GaN/GaMnN resonant tunneling diode

Summary of the results for spin filter



APPLIED PHYSICS LETTERS **102**, 242411 (2013)

Spin filter effect at room temperature in GaN/GaMnN ferromagnetic resonant tunnelling diode

P. Wójcik,[a)] J. Adamowski, M. Wołoszyn, and B. J. Spisak
University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland

Summary of the results for spin filter

242411-2 Wójcik *et al.* Appl. Phys. Lett. **102**, 242411 (2013)

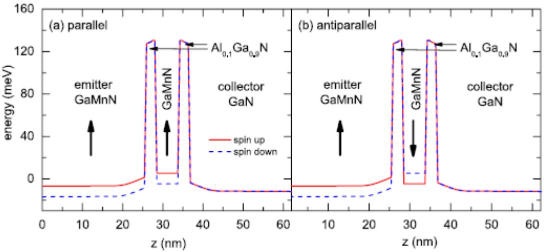


FIG. 1. Self-consistent potential energy profile for spin up and spin down electrons calculated for (a) parallel and (b) antiparallel alignments of the magnetization of the emitter and quantum well layers.

Summary of the results for spin filter

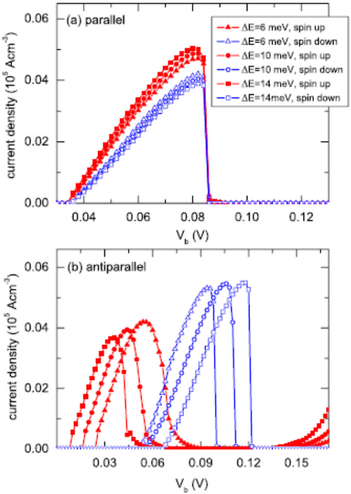


FIG. 2. Current-voltage characteristics for spin up (red) and spin down (blue) current components calculated for different values of the splitting energy ΔE and (a) parallel, (b) antiparallel alignments of the magnetization of the emitter and the quantum well layers at $T = 4.2$ K.

Summary of the results for spin filter

$$\text{spin polarization of the current} = \frac{j_\uparrow - j_\downarrow}{j_\uparrow + j_\downarrow} , \tag{11}$$

j_σ = current density for $\sigma =\uparrow, \downarrow$.

Summary of the results for spin filter

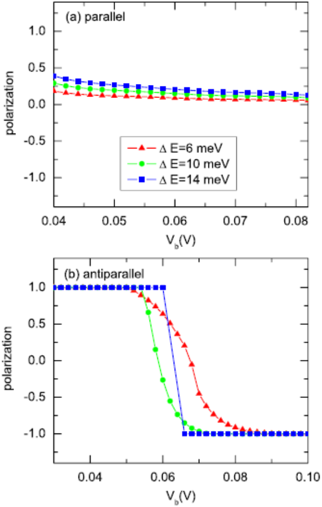
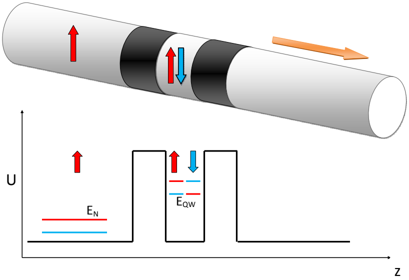
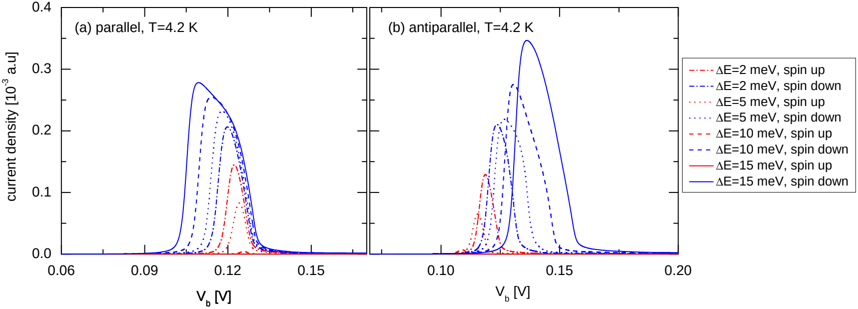


FIG. 3. Spin polarization of current P as a function of bias V_b for different values of splitting energy ΔE and (a) parallel and (b) antiparallel alignments of the magnetization of the emitter and the quantum well layers at $T = 4.2$ K.

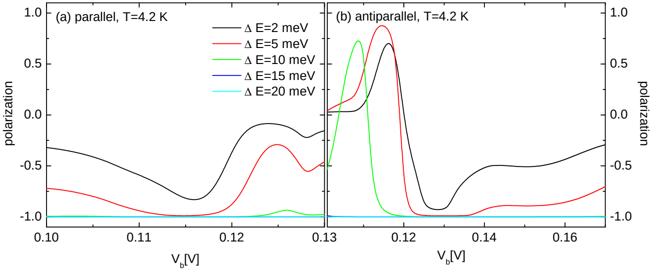
Results for the resonant tunneling diode made from GaN/GaMnN nanowire



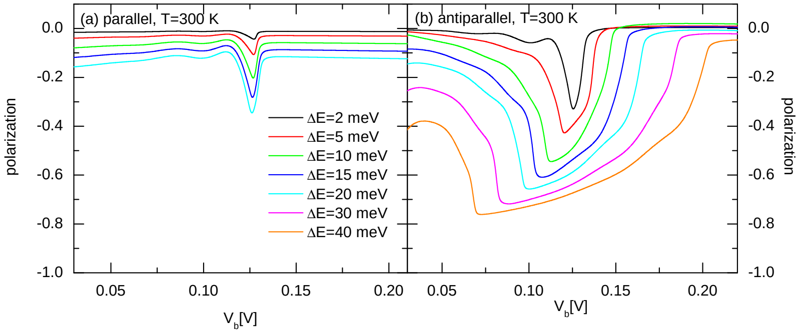
Schematic of the resonant tunneling diode (RTD) based on the ferromagnetic semiconductor nanowire. Emitter (left contact) and quantum well are fabricated from ferromagnetic GaMnN, collector (right contact) – GaN, barriers – AlGaN, ΔE = spin splitting of the conduction band in GaMnN, $\Delta E \sim E_Z$.



Current-voltage characteristics of the nanowire RTD with ferromagnetic contacts at 4.2K. The magnetization of the source and QW regions is (a) parallel (b) antiparallel.

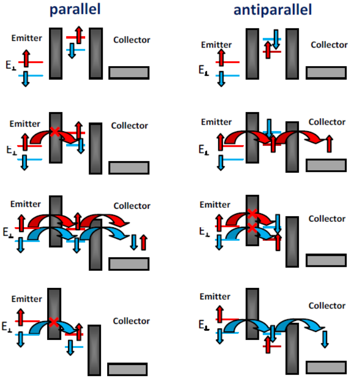


Spin polarization of the current at 4.2K. The magnetization of the source and QW regions is (a) parallel (b) antiparallel.



Spin polarization of the current at 300K. The magnetization of the source and QW regions is (a) parallel (b) antiparallel.

Summary of the results for spin filter



Electron spin transitions in the nanowire with the parallel and antiparallel magnetization of the source and QW regions. The source-drain voltage increases from the top to bottom panel.

Summary of the results for spin filter

- Antiparallel magnetization configuration is preferred for efficient spin polarization.
- Spin current polarization can reach $|P| = 1$ at zero temperature and $|P| = 0.75$ at room temperature.
- The spin filter is an analog of the polarizer (analyzer) of photons.

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III. Spin transistor

III.A. Idea of spin transistor

Analogy between the operation of electro-optic modulator and spin transistor.

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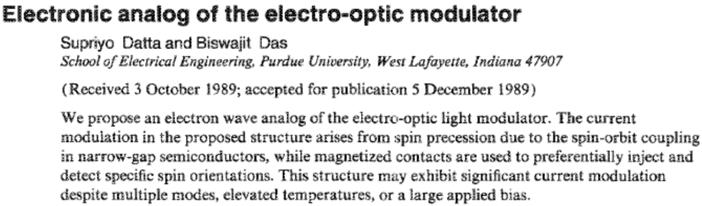


Electronic analog of the electro-optic modulator

Supriyo Datta and Biswajit Das
School of Electrical Engineering, Purdue University, West Lafayette, Indiana 47907

(Received 3 October 1989; accepted for publication 5 December 1989)

We propose an electron wave analog of the electro-optic light modulator. The current modulation in the proposed structure arises from spin precession due to the spin-orbit coupling in narrow-gap semiconductors, while magnetized contacts are used to preferentially inject and detect specific spin orientations. This structure may exhibit significant current modulation despite multiple modes, elevated temperatures, or a large applied bias.

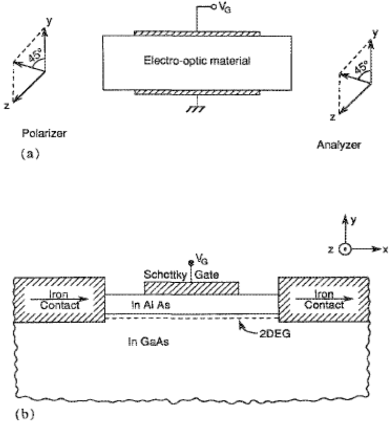
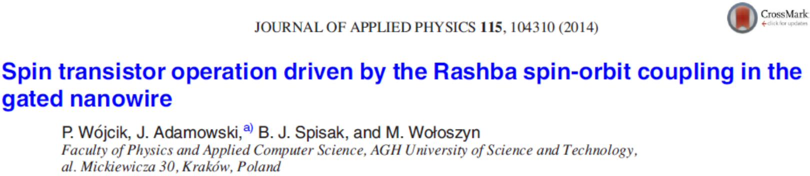


FIG. 1. (a) Electro-optic modulator; (b) proposed electron wave analog of the electro-optic modulator.



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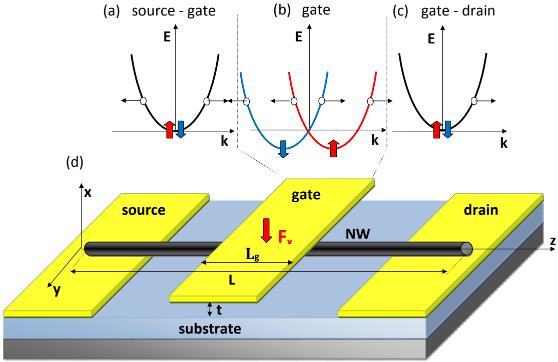
Spin transistor operation driven by the Rashba spin-orbit coupling in the gated nanowire

P. Wójcik, J. Adamowski,[a] B. J. Spisak, and M. Wołoszyn
Faculty of Physics and Applied Computer Science, AGH University of Science and Technology, al. Mickiewicza 30, Kraków, Poland



Schematic of the spin transistor based on the nanowire with the side gate.

III.B. Ideal operation mode

We assume:

- full spin polarization of electrons in source and drain contacts
- zero temperature
- ballistic transport (no scattering)
- conduction via one transverse subband

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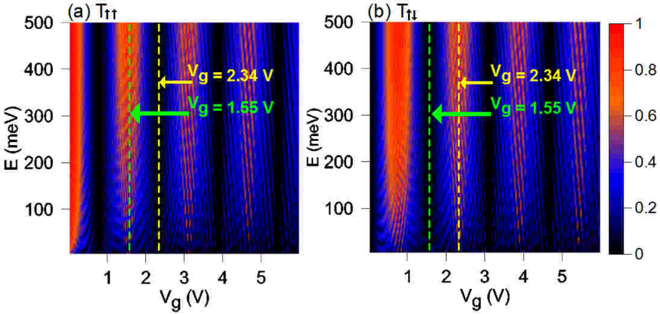
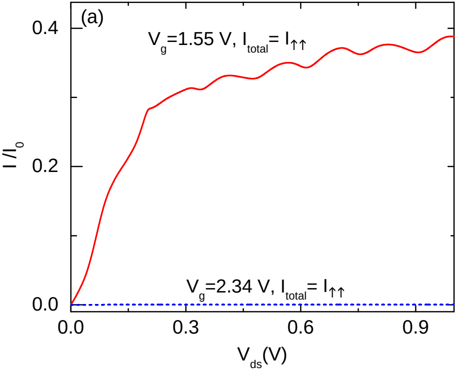
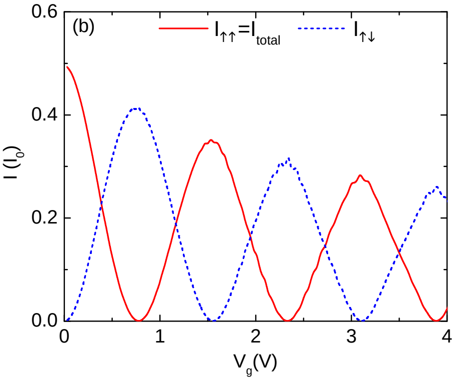


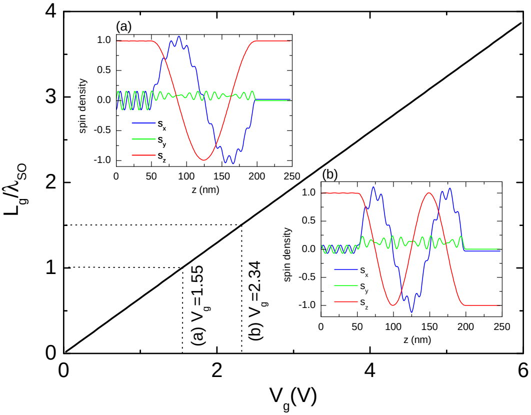
(a) No-spin-flip and (b) spin-flip transmission as a function of gate voltage V_g and energy E of the injected electron.



Current-voltage characteristics of the gated nanowire at 0K.



Current I as a function of gate voltage V_g at 0K.



λ_{SO} = characteristic length for the spin-orbit coupling, L_g = gate length, V_g = gate voltage. After passing length λ_{SO}, the rotating electron spin turns back to its initial state.

(a) Integer (b) half-integer number of s_z spin rotations.

We have found that ratio L_g/λ_{SO} is **the linear function of gate voltage**.

$$\frac{L_g}{\lambda_{SO}} = aV_g \ , \qquad (12)$$

where $a = 0.65 \text{ V}^{-1}$.

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III.C. Realistic operation mode

Spin polarization of electrons in the contacts

$$P = \frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow} \tag{13}$$

n_σ = electron density for spin $\sigma = \uparrow, \downarrow$

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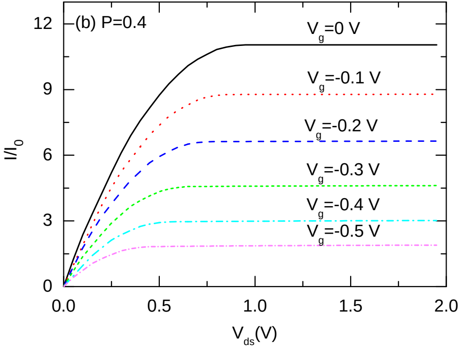
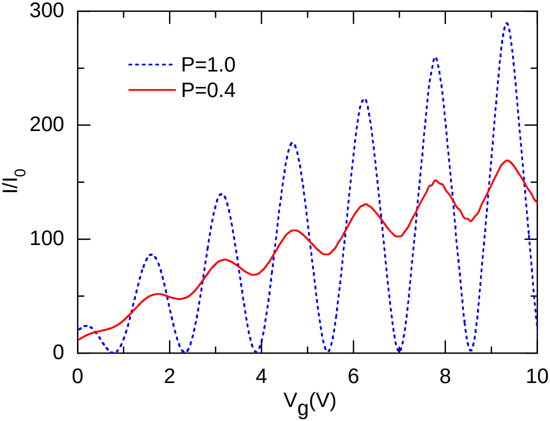


Current-voltage characteristics for the partial spin polarization ($P = 0.4$) at 300 K.

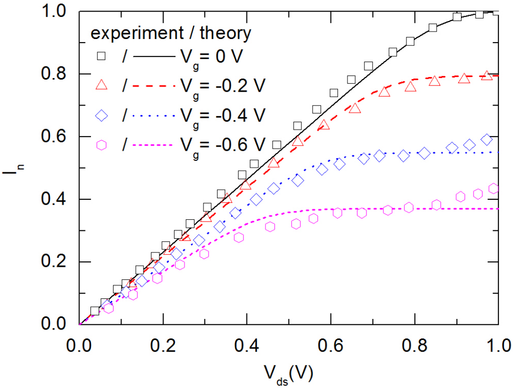


Current I as a function of gate voltage V_g for the full ($P = 1$) and partial ($P = 0.4$) spin polarization at 300 K.

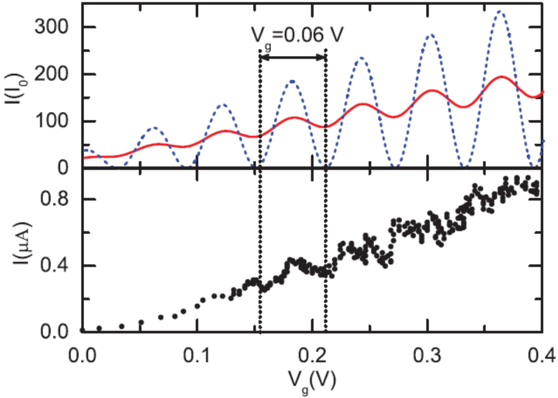
III.D. Comparison with experiment

An InAs Nanowire Spin Transistor with Subthreshold Slope of 20mV/dec

Kanji Yoh1), Z. Cui1), K. Konishi1), M.Ohno2), K.Blekker3), W.Prost3), F.-J. Tegude3), J.-C. Harmand4)
1) Research Center for Integrated Quantum Electronics , Hokkaido University, 060-6828 Sapporo, Japan
2) Graduate School of Engineering, Hokkaido University, 060-6828 Sapporo, Japan
3) Semiconductor and Information Engineering , University of Duisburg-Essen, 47057 Duisburg, Germany
4) CNRS-Laboratory of Photonic and Nanostructures , F-91460 Marcoussis, France
phone: +81 11 706-6872, fax: +81 11 716-6004, email: kanjiyoh@aol.com



Current-voltage characteristics of nanowire spin transistor for $P = 0.4$ and temperature $T = 300$K. Symbols correspond to experimental data of Yoh et al., curves – calculation results.



Current I as a function of gate voltage V_g for $T = 300$K. Upper panel: calculation results for the full ($P = 1$, red solid curve) and partial ($P = 0.4$, blue broken curve) spin polarization. Lower panel: experimental data of Yoh et al.

Period of current oscillations as a function of gate voltage:

$$\Delta V_g^{expt} = \Delta V_g^{calc} = 60\mathrm{mV} \; .$$

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IV. Summary

- In the gated nanowire, the gate voltage modulates the spin-orbit interaction, which changes the electron spins without the external magnetic field.
- $\Longrightarrow$ **All-electric operation.**
- $\Longrightarrow$ Current oscillations as a function of gate voltage.
- $\Longrightarrow$ The current can be switched on/off by tuning the gate voltage (separately for each spin polarization).
- The efficient operation of the spin transistor strongly depends on the spin polarization of electrons in the source and drain contacts.
- $\Longrightarrow$ **Gate-controlled InAs nanowire can operate as the spin transistor.**

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Perfect operation of the spin transistor for each spin polarization.

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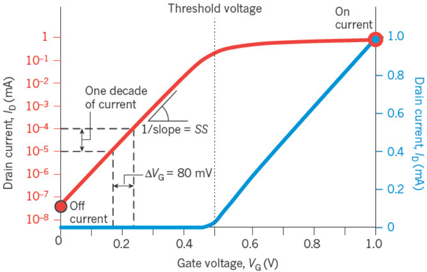

Perfect operation of the conventional field-effect transistor.

I. Ferain et al., Nature 479 (2011) 310.

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Dziękuję Państwu za uwagę.