Physics of heterostructure interfaces as a source for quantum information processing

Martin Gmitra

Institute of Physics, P. J. Šafárik University in Košice

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Contents

• Metallic junctions

semiconductor / ferromagnetic interface

spin-orbit coupling fields in solids magnetic control of the fields semiconducting wires & Majorana bound state story

van der Waals heterostructures

1D semiconductor / 2D superconductor interface

proximity induced spin-orbit coupling effects proposal Majorana bound states in carbon nanotubes

Spin-orbit coupling essentials



Concept of spin-orbit coupling field in solids

time reversal + space inversion symmetry

 $\varepsilon_{{\bf k},\uparrow} = \varepsilon_{{\bf k},\downarrow}$

time reversal symmetry only

$$\varepsilon_{\mathbf{k},\uparrow} = \varepsilon_{-\mathbf{k},\downarrow}, \quad \varepsilon_{\mathbf{k},\uparrow} \neq \varepsilon_{\mathbf{k},\downarrow}$$

 $\Omega(-\mathbf{k}) = -\Omega(\mathbf{k})$

effective k-dependent spin-splitting magnetic field



$$\mathcal{H}_{\rm so}(\mathbf{k}) = \frac{\hbar}{2} \mathbf{\Omega}(\mathbf{k}) \cdot \boldsymbol{\sigma}$$

 $\mathcal{H}_{\mathrm{D}}(\mathbf{k}) = \gamma(\sigma_y k_y - \sigma_x k_x) \longrightarrow \Omega_{\mathrm{BIA}}(\mathbf{k}) = \gamma(-k_x, k_y)$ bulk inversion asymmetry (BIA)

 $\mathcal{H}_{BR}(\mathbf{k}) = \alpha(\sigma_y k_x - \sigma_x k_y) \longrightarrow \mathbf{\Omega}_{SIA}(\mathbf{k}) = \alpha(-k_y, k_x)$ structure inversion asymmetry (SIA)

Combination of the linearized spin-orbit fields

symmetry lowering



 $\mathcal{H}_{\mathrm{D}}(\mathbf{k}) = \gamma(\sigma_{y}k_{y} - \sigma_{x}k_{x}) \longrightarrow \Omega_{\mathrm{BIA}}(\mathbf{k}) = \gamma(-k_{x}, k_{y})$ bulk inversion asymmetry (BIA)

 $\mathcal{H}_{BR}(\mathbf{k}) = \alpha(\sigma_y k_x - \sigma_x k_y) \longrightarrow \Omega_{SIA}(\mathbf{k}) = \alpha(-k_y, k_x)$ structure inversion asymmetry (SIA)

SOC fields in bulk III-V semiconductors



G. Dresselhaus, Phys. Rev. 100, 580 (1955)



J. Y. Fu and M. W. Wu, JAP **104**, 093712 (2008)

Spin-orbit coupling parameters for bulk III-V

extracted parameters for conduction band

| | | GaAs | GaSb | InAs | InSb |
|----------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|-----------------|----------------|---------------|
| zinc-bl | inc-blende | | | | |
| Γ_{6c} | $\begin{aligned} \mathbf{\Omega}(\mathbf{k}) &= \gamma [k_x (k_y^2 - k_z^2), k_y (k_z^2 - k_x^2), k_z (k_x^2 - k_y^2)] \\ \gamma \; [\text{eV Å}^3] \end{aligned}$ | 9.13 | 105.3 | 21.4 | 200 |
| wurtzite [a] [b] | | (47) [b] | (209) [b] | | |
| Γ_{7c} | $oldsymbol{\Omega}(\mathbf{k}) = (lpha + \gamma [bk_z^2 - k_\parallel^2])(k_y, -k_x, 0)$ | | | | |
| | lpha [eV Å] $\gamma [eV Å^3]$ | $0.04 \\ 6.51$ | $0.078 \\ 52.1$ | $0.3 \\ 134.2$ | $0.76 \\ 904$ |
| Гee | $b = (\alpha + \gamma [bk_{-}^2 - k_{-}^2])(k_{-} - k_{-} 0)$ | 0.54 | 1.29 | -1.25 | -0.93 |
| 1 00 | $\alpha [eV Å]$ | 0.1 | 0.49 | 0.04 | 0.34 |
| | γ [ev A°] b | 0.03 | -0.04 | -0.06 | -0.07 |

[a] M.I. McMahon, R.J. Nelmes, Phys. Rev. Lett. **95**, 215505 (2005) [b] D. Kriegner *et al.*, Nano Lett. **11**, 1438 (2011)

[*] A.N. Chantis et al., Phys. Rev. Lett. 96, 086406 (2006)

M. Gmitra, J. Fabian, Phys. Rev. B 94, 165202 (2016)

DFT calculations WIEN2k + mBJ



Spin-orbit fields in zinc-blende

growth directions of quantum wells



Manifestation of spin-orbit fields

magnetoresistive effects

| GMR/TMR (giant magnetoresistance) | GMR/TMR (giant magnetoresistance) | Hall effect | SPAR (spin polarized Andreev reflection) |
|--------------------------------------------------------|------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------|
| TAMR (tunneling anisotropic magnetoresistance) | CAMR (crystalline anisotropic magnetoresistance) | PHE (planar Hall effect) | MAAR (magnetoanisotropic Andreev reflection) |
| AlGaAs GaAs Fe Co Au GaAs substrate | Al ₂ O ₃ MgO Fe GaAs | har the transformed to the trans | Ferromagnet |
| J. Moser <i>et al.</i> , PRL 99 , 056601 (2007) | T. Hupfauer <i>et al.</i> , Nat. Comm. 6 , 7374 (2015) | X. Fan <i>et al.</i> , Nat. Comm. 4 , 1799 (2013) | P. Högl <i>et al</i> ., PRL 115 , 116601 (2015) |

Symmetry of Fe/GaAs (001) interface

advances of epitaxial growth



Exploring symmetry

a path to the effective Hamiltonian



$$E, C_2, \sigma_{xz}, \sigma_{yz}$$

$$H_{\mathrm{plane}} \sim \left(lpha x^2 + eta y^2
ight) imes z$$

$$k_x \sim x, \ k_y \sim y, \quad \sigma_x \sim yz, \ \sigma_y \sim -xz$$

$$H_{so} \sim \alpha k_x \sigma_y + \beta k_y \sigma_x$$

generic linear in k spin-orbit coupling of $\ C_{2v}$



Parameters depend on magnetization

most general Hamiltonian for C_{2v}

$$\mathcal{H}_{so} = \mu_n(k_x, k_y, \theta) k_x \sigma_y + \eta_n(k_x, k_y, \theta) k_y \sigma_x$$

$$\mu_n(k_x, k_y, \theta) = \mu_n^{(0)}(\theta) + \mu_n^{(1)}(\theta)k_x^2 + \mu_n^{(2)}(\theta)k_y^2 + \dots$$
$$\eta_n(k_x, k_y, \theta) = \eta_n^{(0)}(\theta) + \eta_n^{(1)}(\theta)k_x^2 + \eta_n^{(2)}(\theta)k_y^2 + \dots$$

$$\Omega(k_x, k_y, \theta) = \begin{pmatrix} \eta_n(k_x, k_y, \theta) \\ \mu_n(k_x, k_y, \theta) \\ 0 \end{pmatrix}$$



Spin-orbit field obtained from bands

$$\Omega_{nx}(k_x, k_y, \theta) = \sigma \left[\frac{E_n(\mathbf{k}, \theta) - E_n(-\mathbf{k}, \theta) + E_n(-k_x, k_y, \theta) - E_n(k_x, -k_y, \theta)}{4\cos\theta} \right]$$
$$\Omega_{ny}(k_x, k_y, \theta) = \sigma \left[\frac{E_n(\mathbf{k}, \theta) - E_n(-\mathbf{k}, \theta) - E_n(-k_x, k_y, \theta) + E_n(k_x, -k_y, \theta)}{4\sin\theta} \right]$$



M. Gmitra et al., PRL 111, 036603 (2013)

100

Magnetic control of spin-orbit symmetry

spin-orbit field for general k-point



k = 1% BZ

k = 12.5% BZ

M. Gmitra et al., PRL 111, 036603 (2013)

Symmetry of Fe/GaAs (001) interface

addressing the spin-orbit field by optics

anisotropic polar MOKE – Kerr rotation



S. Putz et al., Phys. Rev. B 90, 045315 (2014)

M. Buchner et al., Phys. Rev. Lett. 117, 157202 (2016)

Crystalline anisotropic magnetoresistance



$$CAMR(\theta) = \frac{U_{max}(\theta) - U_{min}(\theta)}{U_{max}(\theta) + U_{min}(\theta)}$$



 $\mathrm{CAMR}(\theta) \,\approx\, \frac{B+C+(C-B)\mathrm{cos}(4\theta)-4F\mathrm{cos}(2\theta)}{4A}$





reduction of Fe thickness

T. Hupfauer et al., Nat. Comm. 6, 7374 (2015)

Spin-orbit field in core/shell wurtzite nanowires

role of GaAs/AlGaAs interface



- pioneering optical spin injection into a single free-standing nanowire
- *g*-factor significantly different than in the cubic zinc-blende phase
- highly anisotropic spin relaxation due to SOC at core/shell interface

S. Furthmeier et al., Nat. Comm. 7, 12413 (2016)

Conduction subbands in nanowires (50 nm)

an element for Topological Quantum Computation



Topological Quantum Computation

approach to fault-tolerant quantum computation



Localized excitations on an interacting Hamiltonian

(Laughlin fractional Quantum Hall liquid)

• Defects in an ordered system

(Abrikosov vortices in topological superconductor / domain wall in 1D system)

simplest realization of non-Abelian anyons (no anionic excitations) is a quasiparticle or defect supporting a **Majorana zero mode** (zero energy mid-gap excitation)

What is the Majorana zero mode?

zeroth order crash course

- is a fermionic operator γ • squares to unity $\gamma^2 = 1$
 - Majorana fermion

- commutes with the Hamiltonian of a system
- degenerate ground state / non-local entanglement
- decomposition to conventional fermions

 $[\gamma, H] = 0$ $\{\gamma_i, \gamma_j\} = 2\delta_{ij}$ $c_j = \frac{1}{2}(\gamma_{2j-1} + i\gamma_{2j})$

To realize Majorana excitations $\gamma = \gamma^{\dagger}$ we seek for, e.g., $\gamma = uc + vc^{\dagger}$ with energy dependent coefficients of Bogoliubov quasiparticle excitations

BCS **spinless** fermion pairing → Cooper pair wave function must be **antisymmetric** therefore Majorana zero-energy excitations should exist in *p*-wave superconductors

Spinless *p*-wave superconductors

continuum mean-field many-particle Hamiltonian

$$\mathcal{H} = \int dx \left\{ \psi^{\dagger}(x) \left(\frac{p^2}{2m} - \mu \right) \psi(x) + \Delta' [\psi^{\dagger}(x) \partial_x \psi^{\dagger}(x) + \text{h.c.}] \right\}$$

associated Bogoliubov—de Gennes Hamiltonian

$$H = \begin{pmatrix} \xi_p & -i\Delta'p \\ i\Delta'p & -\xi_p \end{pmatrix} = \xi_p \tau_z + \Delta' p \tau_y \quad \text{where} \quad \xi_p = p^2/2m - \mu$$

excitation spectrum for an infinite system

$$E_k = \pm (\xi_k^2 + {\Delta'}^2 k^2)^{1/2}$$

effective BdG field in particle-hole space

$$H_k = \mathbf{b}_k \cdot \mathbf{\tau}_{\mathbf{v}}$$

$$\hat{\mathbf{b}}_k = \mathbf{b}_k / ||\mathbf{b}_k|| = igg($$

$$\begin{pmatrix} 0 \\ \Delta' k / \sqrt{(\Delta' k)^2 + \xi_k^2} \\ \xi_k / \sqrt{(\Delta' k)^2 + \xi_k^2} \end{pmatrix}$$

Pauli matrices in particle-hole space

Spinless *p*-wave superconductors

$$E_k = \pm ((k^2/2m - \mu)^2 + \Delta'^2 k^2)^{1/2}$$



$$\hat{\mathbf{b}}_k = \begin{pmatrix} 0 \\ \Delta' k / \sqrt{(\Delta' k)^2 + \xi_k^2} \\ \xi_k / \sqrt{(\Delta' k)^2 + \xi_k^2} \end{pmatrix}$$





Domain wall Majorana excitations



"Synthetic" realization of Majorana excitations

experimentally accessible system

Basic ingredients:

- 1. proximity coupling to s-wave superconductor
- 2. spin polarization
- 3. spin-orbit coupling

$$g\mu_{\rm B}B > \sqrt{\Delta^2 + \mu^2}$$

Carbon nanotube hosts Majorana zero mode

novel proposal



^[*]M. Marganska et al., arXiv: 1711.03616v1

2H polytype of NbSe₂



- SG: #194 (P6₃/mmc)
- PG: D_{6h}
- $a = 3.445 \text{ Å}^{[*]}$
- c = 12.55 Å

^[*]J. Xu et al., Digest Journal of Nanomaterials and Biostructures **10**, 505 (2015)

Anisotropic type-II superconductor



^[*]J. A. Galvis et al., arXiv:1711.09269 (2017)



^[*]M. Leuroux et al., PRB **92**, 140303 (2015)



^[*]G. Gruener, Rev. Mod. Phys. **60**, 1129 (1988)

3x3 CDW in single layer NbSe₂



^[*]M. M. Ugeda et al., Nat. Phys. **12**, 92 (2016)

Peeling-off NbSe₂ layer-by-layer



^[*]X. Xi et al., Nat. Nanotech. **10**, 765 (2015)

Ising pairing by spin-momentum locking





Fermi surface/superconductivity





or two-band superconductivity?

anisotropic gap

^[*]Y. Noat et al., PRB **92**, 134510 (2015)

Coupling of two sub-systems



Interaction of two bands



^[*]solution:
$$E_{1,2} = \frac{1}{2} \left[\epsilon_s + t \cos(k) \pm \sqrt{\epsilon_s^2 + 4V^2 - 2\epsilon_s t \cos(k) + t^2 \cos^2(k)} \right]$$

What would see ARPES?

$$\begin{split} G_{11}^{\mathrm{R}}(\omega,k) &= \frac{1}{\omega - t\cos(k) + i\eta - V^2 g_2^{\mathrm{R}}} & & \\ G_{22}^{\mathrm{R}}(\omega,k) &= \frac{1}{\omega - \epsilon_{\mathrm{s}} + i\eta - V^2 g_1^{\mathrm{R}}} & & \\ \Sigma_{11}(\omega,k) &= V^2 g_2^{\mathrm{R}} & & \\ \Sigma_{22}(\omega,k) &= V^2 g_1^{\mathrm{R}} & & \\ A(\omega,k) &= \sum_i A_i(\omega,k) & & \\ A_i(\omega,k) &= \frac{-2\mathrm{Im}[\Sigma_{ii}(\omega,k)]}{(\omega - \epsilon_i(k) - \mathrm{Re}[\Sigma_{ii}(\omega,k)])^2 + (\mathrm{Im}[\Sigma_{ii}(\omega,k)])^2} & \\ \end{split}$$

PERIODIC TABLE OF CARBON NANOTUBES

(2.9) (1.4) (3.6) (4.0) (5.0) 05.00 (7,0) (8.0) (2.0) (10.0) (11.9) (12.0) (13.0) (14.0) (15.0) (16.0) (17.0) 1:111:57 2:2 2.35 9.9 7.83 10:10 8.62 0.78 3:3 3.13 4:4 3.92 55 4.70 676 5.48 7:7 6.27 8:8 7.05 11:11 9.40 12:12 10:18 13:13 10:07 14:14 11:75 15:15 12:54 16:16 13.32 17:17 5424 8,717 0.740 2.570 1.087 0.082 1.494 0.185 1.463 0.827 1.017 0.046 0.643 0.778 0.000 0.552 0.629 0º 4.26 4.26 09 4.26 02 4.26 0^{6} 4.26 62 4.26 0* 4.26 0° 4.26 0° 4.26 09 4.26 02 4.26 02 4.26 02 4.26 00 4.26 - 0° 4.26 62 4.26 02 4.76. 0 44 12. 16 20 24 28 32. 36. 40 48. 52 56 60 6.016.11 (2.1) (10.1) and (12.1) (13.1) (14.1) (15.1) 16.11 (3,1) (4, 1) (7,1)68.10 1:3 4.36 1:1 5,14 1:1 5.91 1:3 6.69 1:1 7.47 1:1 8.25 13 9.04 1:1 9.82 1:1 12.16 1.36 13 2.07 1:1 2.82 1:1 3.59 1:1 10.60 1:3 11.38 1:1 12.94 1:3 13.73 0.058 0.737 2.523 3.594 0.267 1.319 1.821 0.110 0.947 1,188 0.877 0.036 0.608 0.693 0.024 0.510 0.0 651 10.9° 23.74 8.9° 27.95 7.6° 10.73 6.5° 36.42 5.8° 40.67 5.2° 14.97 4.7° 49.16 4.3° 53.42 4.0° 19.22 3.7° 61.92 3.4° 66.18 3.2° 23.48 3.0° 74.69 2.8° 11.28 19.1* 15.37 13.9* 2.46 307 172 76 292 148 532 628 (6.2) 17.25 (14.2) (4.2) (5.2) 64.25 (9.2) (10.21 (11.2) (12.2) (13.2) (2,2)(3.2)1:1 4.15 2:2 4 89 1:3 5.65 2:2 6.41 1:1 7.18 2.6 7.95 1:1 8.72 22 9.50 1:3 10.27 2:2 11.05 1:1 11.83 2.6 12.61 2.2 2.71 2:6 3.41 11 13.39 1,139 1,380 0.057 0.0 1.975 2.146 0.114 0.836 0.990 0.041 0.665 0.766 0.027 0.553 0.623 18.58 23.4° 11.28 19.1° 8.87 16.1° 15.37 13.9° 34.89 12.2° 6.51 10.9° 43.26 9.8° 23.74 8.9° 17.23 8.2° 27.95 7.6° 60.14 7.1° 10.73 6.6° 68.61 6.2° 36.42 5.8° 2.46 30% 248 (10,3) 56 1036 52 104 268 412 196 344 152 (9.3) (12.3) 64.35 (6.3) (7.3) (8.3) 1:1 10:00 3.9 4.77 1:1 5.48 1:1 6.22 3:3 6.96 1:1 7.72 1:1 8.47 3:3 9.24 1:1 10.77 3:9 11.54 1:1 12.31 4.07 1:1 13.9 3:3 13.66 0,744 0.844 1.529 0.057 0,980 1,104 0.043 0.030 0.604 0.678 0.021 0.0 1,509 0.510 30° 25.93 25.3° 29.84 21.8° 11.28 19.1° 37.89 17.0° 41.99 15.3° 15.37 13.9° 50.26 12.7° 54.43 11.7° 5.51 10.9° 62.80 10.2° 67.00 9.5° 23.74 8.9° 75.42 2.46 556 (10,4) 316 652 155 (4.4) (5.4) (6.4) 0.4 (8.4) (OA) (HA) (12.4) (13.4) (14.4) 22 7.56 1:3 8.29 444 9.04 1:1 9.79 2.6 10.54 5.43 4:12 6.12 1:1 6.83 1:1 11.30 4/4 12.05 1:3 12.83 2:2 13.59 1:1 1,191 0.032 0.852 0.919 0.028 0.668 0.734 0.022 0.0 1,205 0.553 0.606 (nam) 80° 33.30 26.3° 18.58 23.4° 13.70 21.1° 11.28 19.1° 49.16 17.5° 8.87 16.1° 57.35 14.9° 15.37 13.9° 21.88 13.0° 34.89 12.2° 73.96 11.5° 2.46 440 112 532 . 104 724 208 3:16 dist. 152 124 536 1204 (8,5) (9.5) (10.5) (11.5) (12.5) (13.5) (6.5) (7.5) $E_{\alpha}(eN)$ 5:15 7.47 1:1 10.36 1:1 8.18 1:1 8.90 1:3 9.63 6.87 5:5 11.11 1:3 11.86 1:1 12.61 1:1 13.36 4:12 14.12 7 (Å) 1,000 0.978 0.020 0.749 0.788 0.020 0.604 0.649 0.016 0.508 0.0 2.46 30° 40.67 27.0° 44.51 24.5' 16.14 22.4° 52.38 20.6° 11.28 19.1° 20.15 17.8° 64.51 16.6° 68.61 15.6° 24.24 14.7° 15.37 13.9° 172 916 1036 604 140 268 (8.4) (10.6) (9,6) (11, 6)12.60 8.14 6:18 8.83 1:1 9.53 2:2 10.24 3:3 10.97 2:2 11.70 1:1 12.44 6:6 13.18 1:1 13.93 2.2 The semi-empirical bandgap E, is calculated following H. Yorkawa and S. Maramatsu, Phys. Rev. B 52, 2723. 0.853 0.830 0.013 0.667 0.014 0.550 0.581 10.0 0.689 (1995) for the semiconducting tubes ino curvature effects; |Vers|-2.7 and y 0.43) and A. Kleiner and S. 302 48.04 27.5* 25.93 25.3* 18.58 23.4* 29.84 21.8* 63.66 20.4* 11.28 19.1* 71.71 18.0* 37.89 17.0* 2.45 228 \$92 164 11322 values are evaluated from the expressions below. (9.7) 100,7) (14.7) (8.7) (11.7)(12.7) 1:1 11.59 1:3 14:51 9.50 7:21 10.18 1:1 10.88 1:3 12.31 1:1 13.04 1:1 13.77 0.0 0.743 0.722 0.009 0.600 0.613 0.011 0.505 cathon-rathon distance: oc. c = 1.021 Å (graphits) 30° 55.42 27.8° 59.22 25.9° 21.03 24.2° 67.00 22.7° 70.95 21.4° 24.98 20.2° 2.46 11.28 19.1 $a = \sqrt{3}a_{C,C} = 2.461 \text{ Å}$ 676 772 292 9.8.8 1108 412 integlia of suilt vectors metallik tube (9.8) (10.8) (12.8) (13,8) (8.8) 01.0 10.86 8.24 11.54 1:1 12.24 22 12.94 1:3 13.66 4:4 14.38 1:1 $a_1 = (\sqrt{3}, +1)a/2$ and $a_2 = (\sqrt{3}, -1)a/2$ and: weeters: 0.545 0.552 in n 0.658 0.639 0.007 reciproced unit vectors: $b_1 = (1/\sqrt{1}, \pm 1)2\pi/a$ and $b_2 = (1/\sqrt{3}, \pm 1)2\pi/a$. 30% 62.80 28.1" 33.30 26.3" 2.45 23.48 24.8% 18.58 23.4^b 78.26 22.2 oblight montents $G_n = m_1 - m_2$ (where $n, m \in \mathbb{Z}$). (10.9) 01.97 (13.9) (9.9) (12.9) semimetallic tube 12.21 9.27 12.99 1:1 13.59 1:1 14.30 3:3 15.01 1:1 $L = |C_{\lambda}| = \alpha \sqrt{\alpha^2 + m^2 + \alpha \omega}$ (where $0 \le m \le \alpha$). circumference of tabe: 0.573 0.498 0.0 0.590 0.005 disapcter of tube: $d_0 = L/\pi$ 70.18 28.3* 73.96 26.7* 25.93 25.3* 81.67 24.0* 2.45 308 chiral angle: $\theta = \omega(\alpha_1, C_h) = \arctan \frac{m\sqrt{3}}{2m - m} \in [0^\circ, 30^\circ]$ 1204 semiconducting tube (10,10) (11, 10)112.100 13.57 10:30 14:25 1:1 14.95 1:1 highest constron divisor of n, m: $d = \ln d(n, m)$ 0.535 0.520 0.0 30* 77.56 28.42 40.67 27.05 2.46 highest common divisor of 2n + m, 2m + m de = hed(2n + m, 2m + m)1324 728 d , if m we is not a multiple of 34 (11,11) (12, 11) 3d , if a -- in is a multiple of 2d 14.93 11:33 15.61 Quantum of 0.849 0.0 transformed vector of 1D and ord: $T = t_1 a_1 + t_2 a_2$ (where $t_1, t_2 \in \mathbb{Z}$) 2.46 30° 84.94 28.6° $h = 1.26 \pm 0.066$ - (2n) milde South of T: $T = |T| = L\sqrt{3}/d_{ee}$ When every atom math number of atoms per 1D will call: $N = (2L)^2/(a^2d_F)$, and N/2-beingona/unit cell

www.guantumwise.com

Chiral carbon (8,4) nanotube





diameter of 8.3 Å 112 atoms in unit cell^[**]

[*]source: https://en.wikipedia.org/wiki/Carbon_nanotube
[**]input: TubeGen3.3, J T Frey, University of Delaware

Band structure of cnt(8,4)



Joint spaghetti





Spin-orbit coupling form



Spin-orbit coupling form



Save the Majoranas!



 $^{[^{\star}]}\textsc{Note:}$ magnetic splitting in 10 Tesla would be 1 meV

Ultrathin films of superconductors

a platform for topological superconducivity (Pb or β -Sn)

- Cooper pairing
- broken inversion symmetry
- broken time-reversal symmetry



Advantage: *interface or proximity effect free* system to obtain SC in a strong SOC systems

C. Lei, H. Chen, A.H. MacDonald, arXiv:1801.05020



large *g*-factor E-field 0.1 V/nm strain of 1%

- ~ 100 350
- ~ 2 meV subbands shift
- ~ 200 meV Fermi level tunning

SC metal Film

$$w/2N \simeq \delta \varepsilon_{2D}$$

 $H_{\mathrm{c},\perp} \approx 1.6 \,\mathrm{T} \qquad H_{\mathrm{c},\parallel} \approx 55 \,\mathrm{T}$







Conclusions

- symmetry dictates topology of spin-orbit coupling fields
- **appreciable proximity** induced spin-orbit coupling effects in vdW heterostructures •
- carbon nanotubes could host Majorana bound states •
- promising topological superconductivity in thin films of heavy elements

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