Зеркальное Андреевское отражение

Э.В. Девятов,
Институт физики твердого тела РАН, Черноголовка,

План лекции

- *Андреевское отражение*
- *Металл, диэлектрик, полуметалл*
- *Зеркальное Андреевское отражение на границе между сверхпроводником и двумерным полуметаллом.*
- *Полуметалл Вейля*

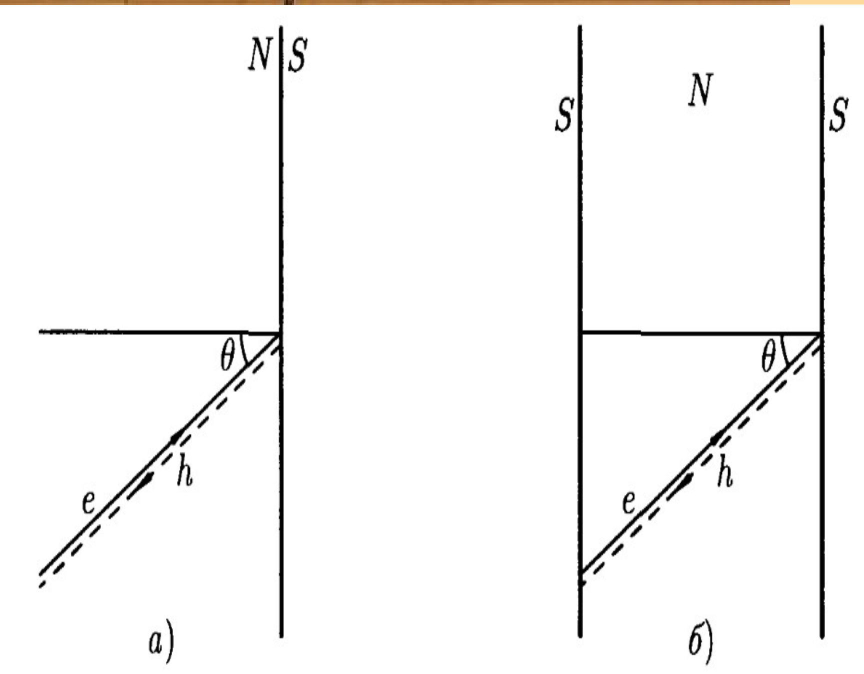
Фундаментальные результаты физики твёрдого тела

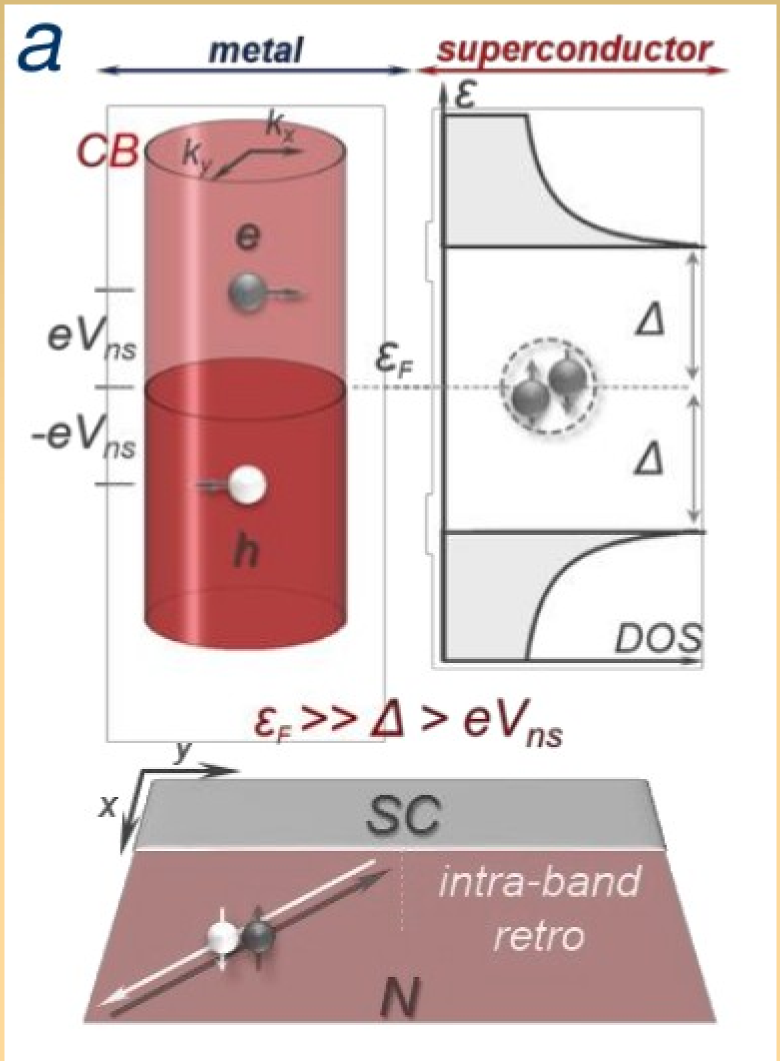
XX век - макроскопические квантовые эффекты

- ***Сверхпроводимость***
- ***Физика низкоразмерных систем (квантовый эффект Холла)***

XXI век - топологические эффекты

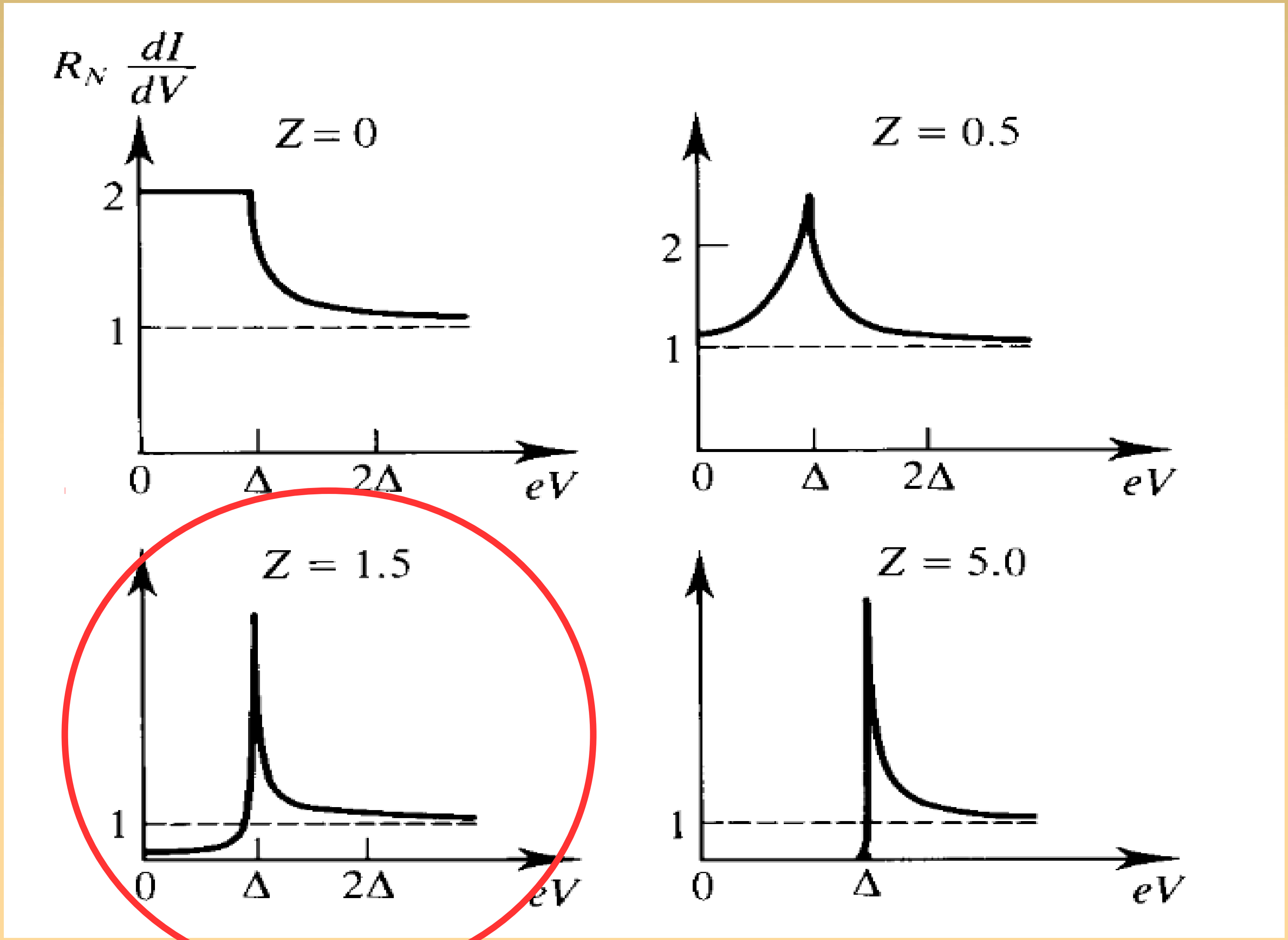
Андреевское отражение





D. K. Efetov, L. Wang, C. Handschin, K. B. Efetov, J. Shuang, R. Cava, T. Taniguchi, K. Watanabe, J. Hone, C. R. Dean, P. Kim, Nature Physics (2015)

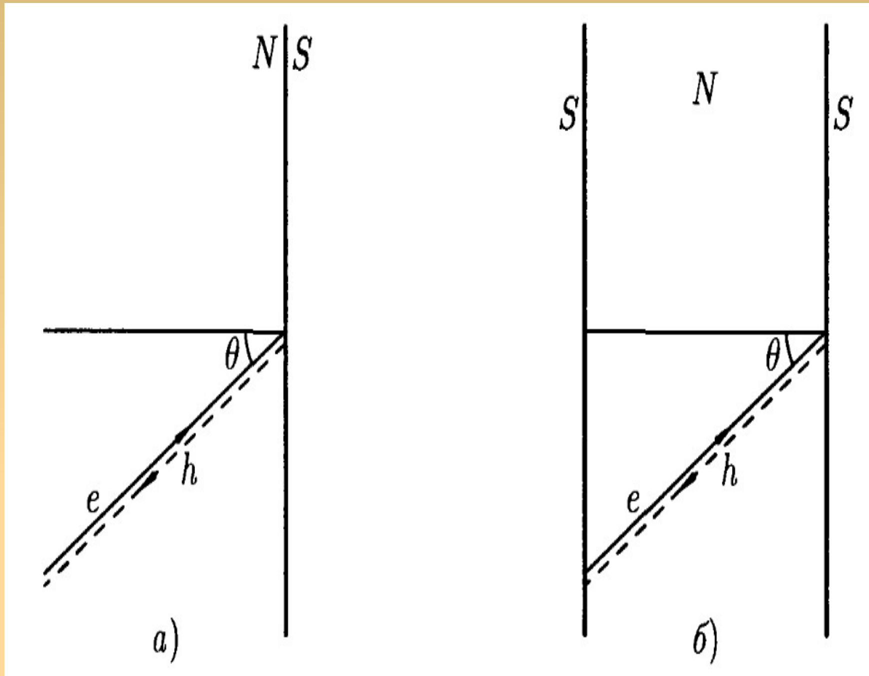
SN contact: Andreev reflection (BTK)



Teun Klapwijk

BTK (G.E. Blonder, M. Tinkham, T.M. Klapwijk, Physical Review B. 25, 4515, (1982))
M. Tinkham, Introduction to Superconductivity (2d ed., McGrawHill, New York, 1996).

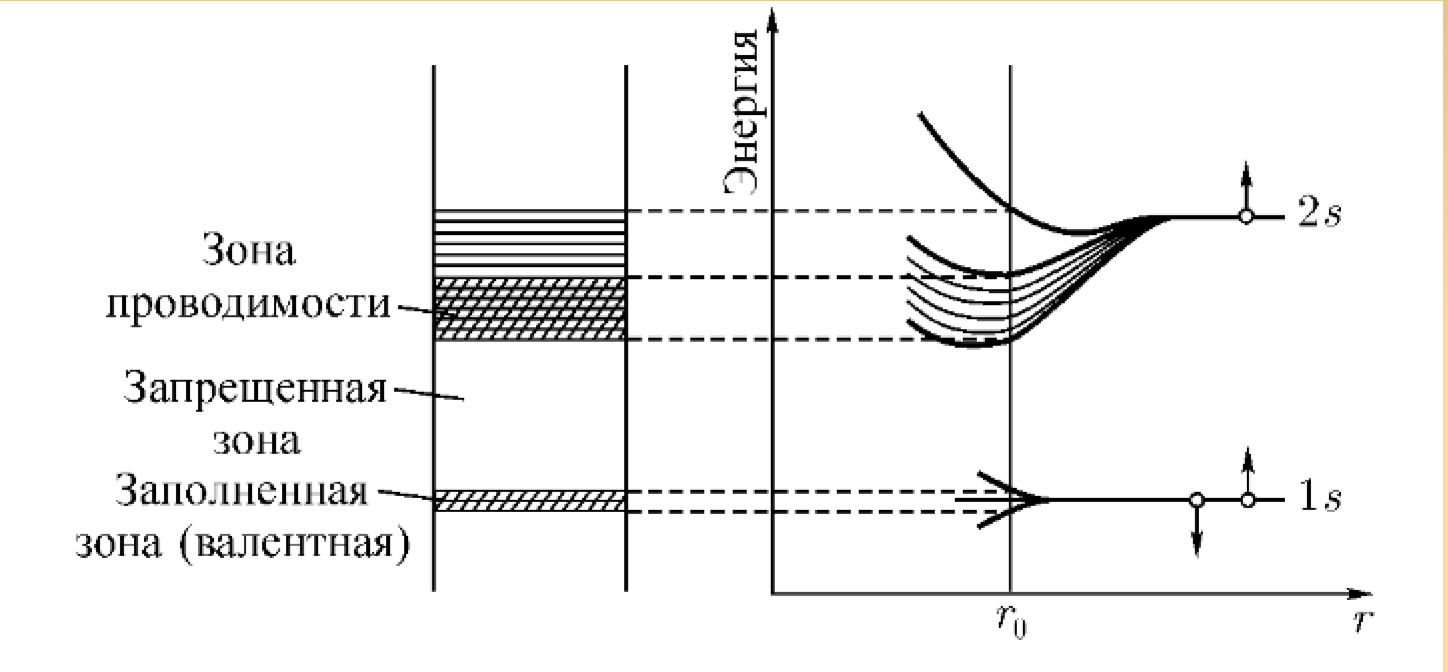
Дырки бывают разные...



О каких дырках мы говорим?

M. Tinkham, Introduction to Superconductivity (2d ed., McGrawHill, New York, 1996)

Электрон в периодическом потенциале. Зонная структура



Дж. Займан, Принципы теории твердого тела, учебник

Заполнение квантовых состояний.

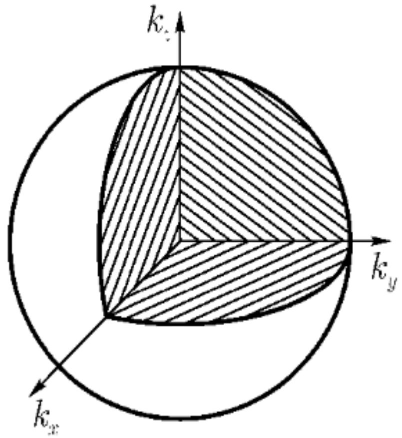


Рис. 82. К расчету числа состояний. Сфера в пространстве волновых чисел.

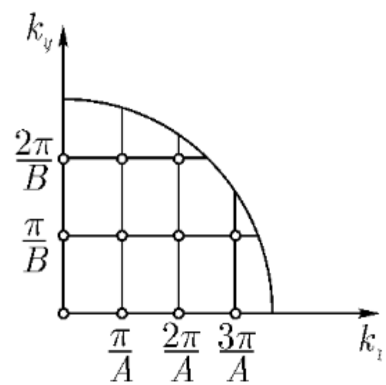
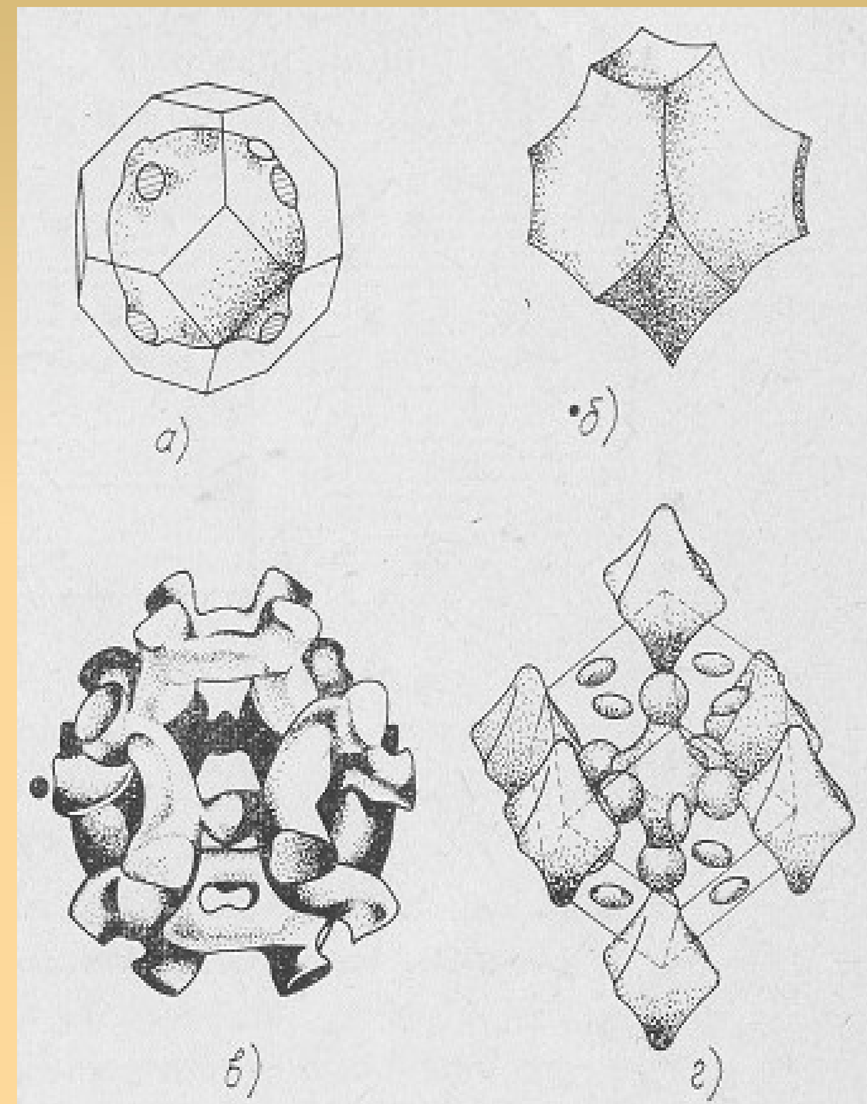


Рис. 83. К расчету числа состояний. «Разрешенные точки» на плоскости волновых чисел.



Дж. Займан, Принципы теории твердого тела, учебник

Металл, диэлектрик, полупроводник. Зонная структура

Металл – зона проводимости частично заполнена

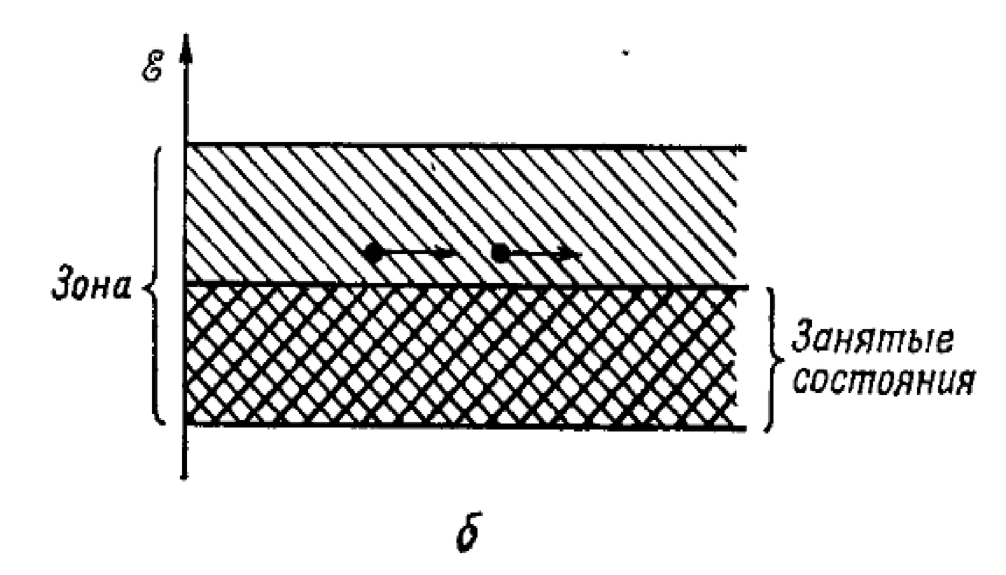
Диэлектрик – зона проводимости пуста, валентная зона заполнена полностью

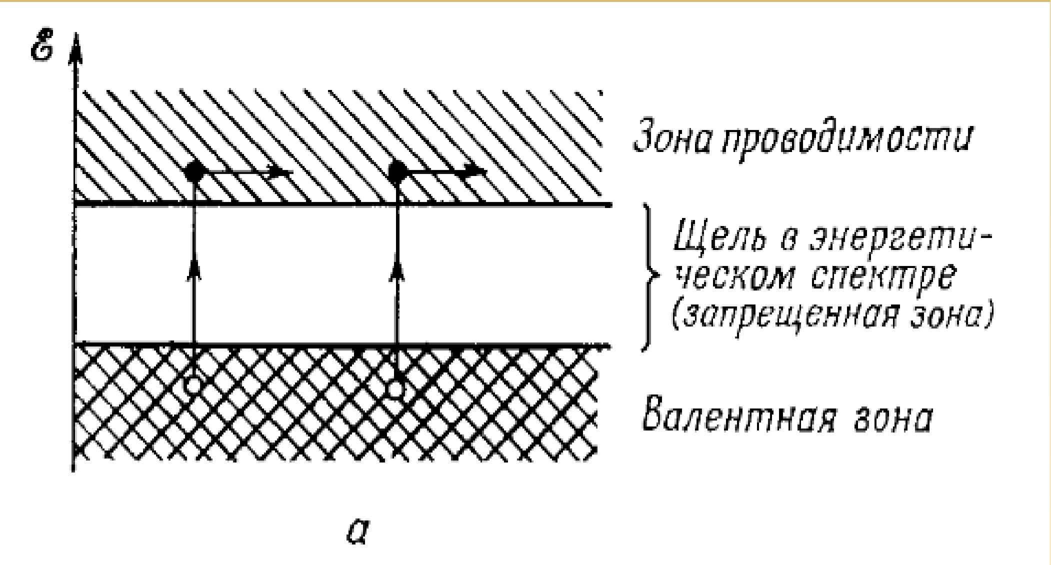
Полупроводник – диэлектрик, у которого ширина запрещённой зоны сравнима с температурой эксперимента (появление активационной проводимости)

Электроны и дырки

- ***Дырки в зоне проводимости***
- ***Дырки в валентной зоне***

Электроны и дырки



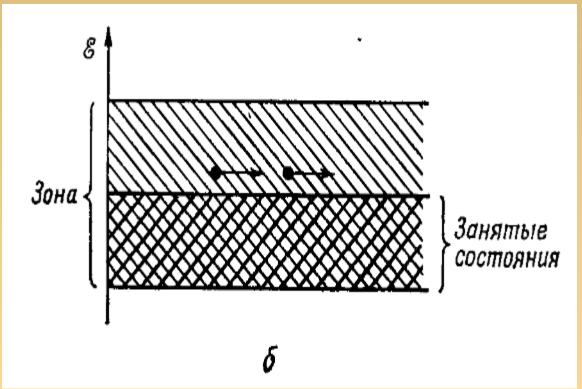


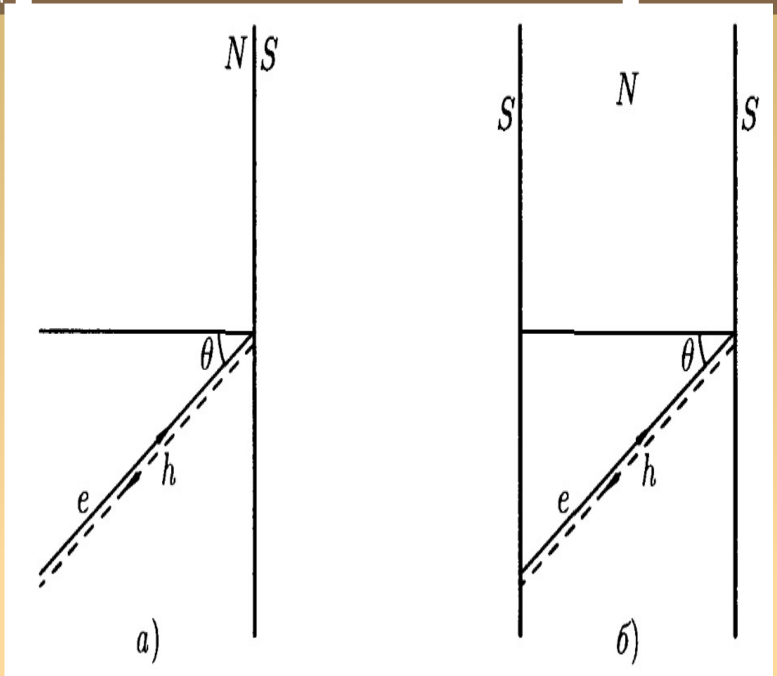
The metal-like hole remains in the conduction band of the normal metal,
and therefore necessarily carries the opposite sign of the mass as compared to the electron.

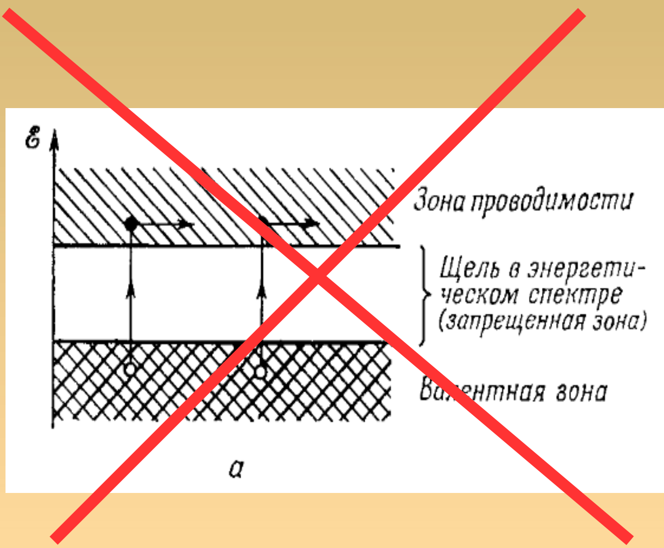
The semiconductor-like hole now has the same mass sign as the electron

Дж. Займан, Принципы теории твердого тела, учебник

Ретро (обычное) Андреевское отражение







For a straight N/SC interface, the momentum conservation along the boundary must be conserved.

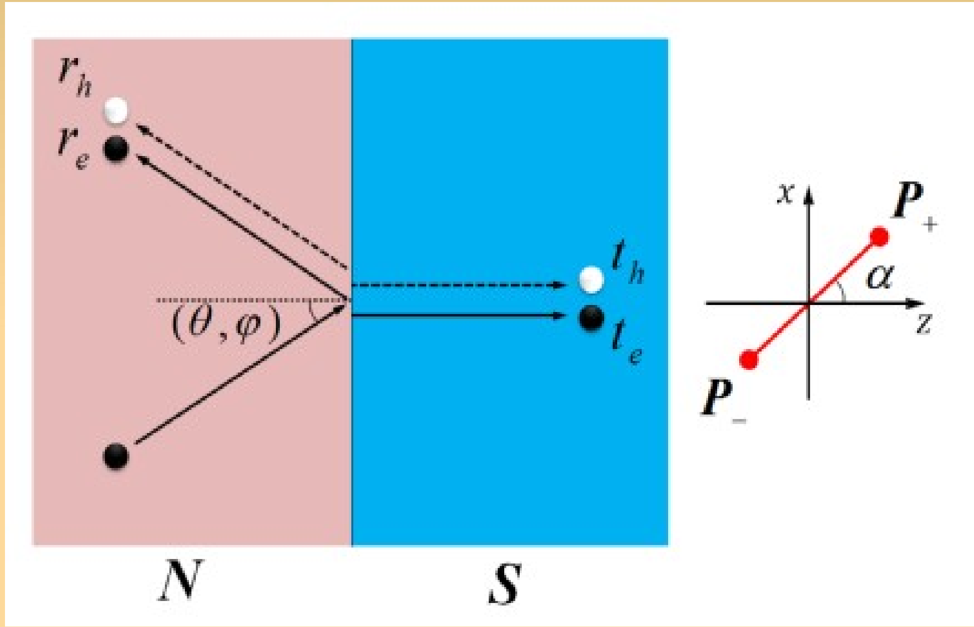
Thus the incidence angle of an incoming electron, θ_{inc} , and the reflected angle of a hole, θ_{ref} , have a simple relation $p_e \sin\theta_{inc} = p_h \sin\theta_{ref}$, where p_e and p_h are the total momentum of the electron and hole, respectively.

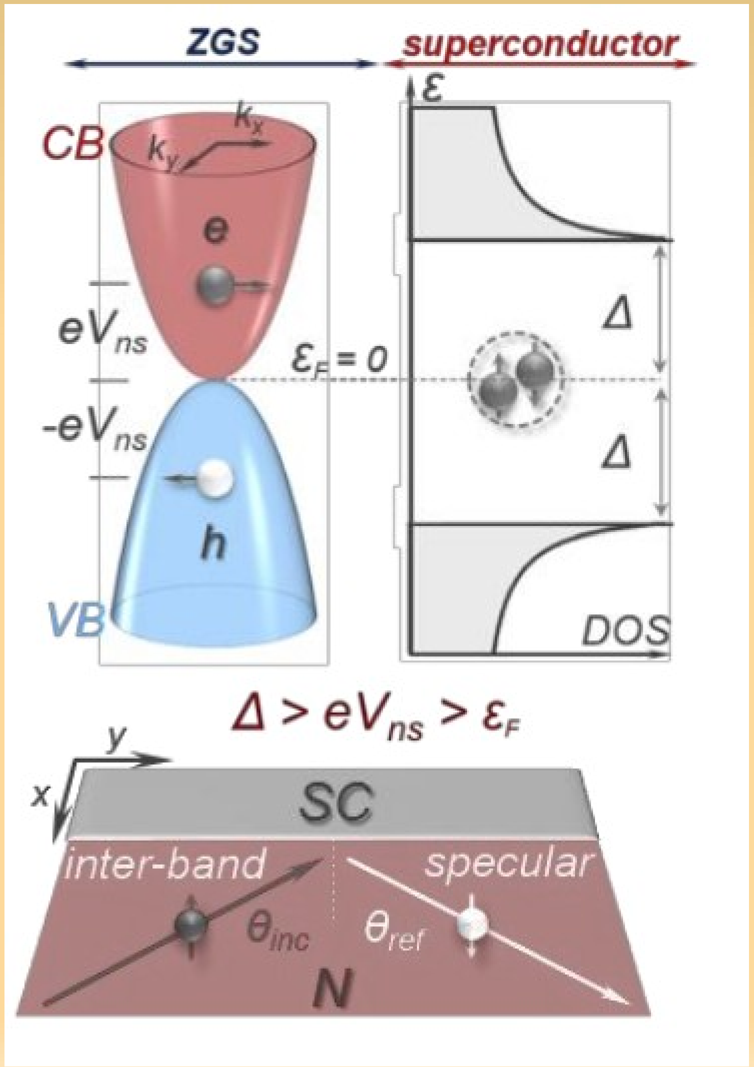
In the limit $\varepsilon_F \gg \Delta$, which holds for a typical NS junction, the reflected hole is metal-like and remains in the conduction band of the normal metal, and therefore necessarily carries the opposite sign of the mass as compared to the electron.

To conserve the momentum, the hole reflects back along a path of the incident electron, exhibiting nearly perfect retro-AR, with $\theta_{ref} \approx -\theta_{inc}$

Спекулярное (зеркальное) Андреевское отражение

C. W. J. Beenakker, Physical Review Letters 97 (2006).
C. W. J. Beenakker, Reviews of Modern Physics 80, 1337 (2008).





D. K. Efetov, L. Wang, C. Handschin, K. B. Efetov, J. Shuang, R. Cava, T. Taniguchi, K. Watanabe, J. Hone, C. R. Dean, P. Kim, Nature Physics (2015)

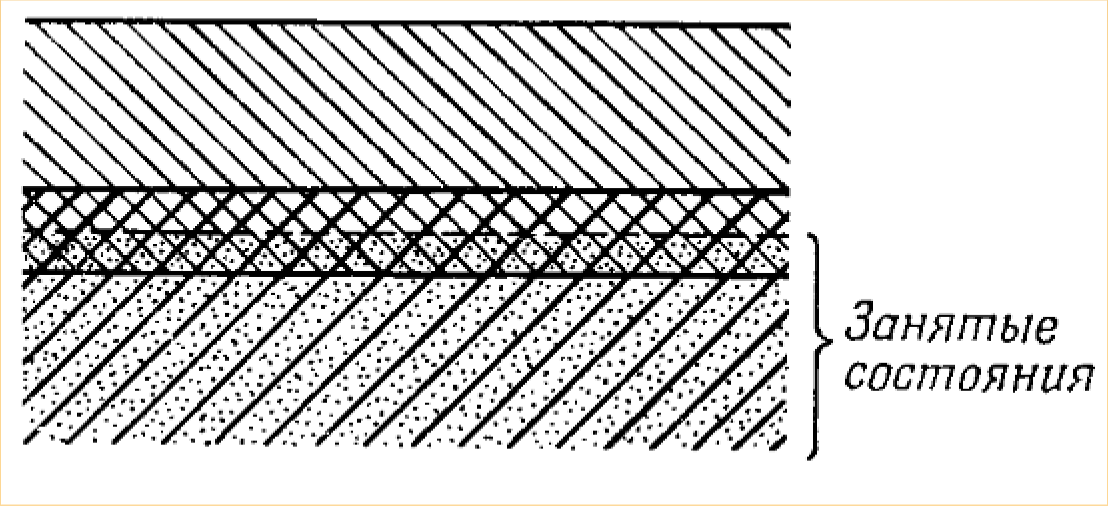
Реализация
Phys. Rev. B 93, 041303(R) (2016)

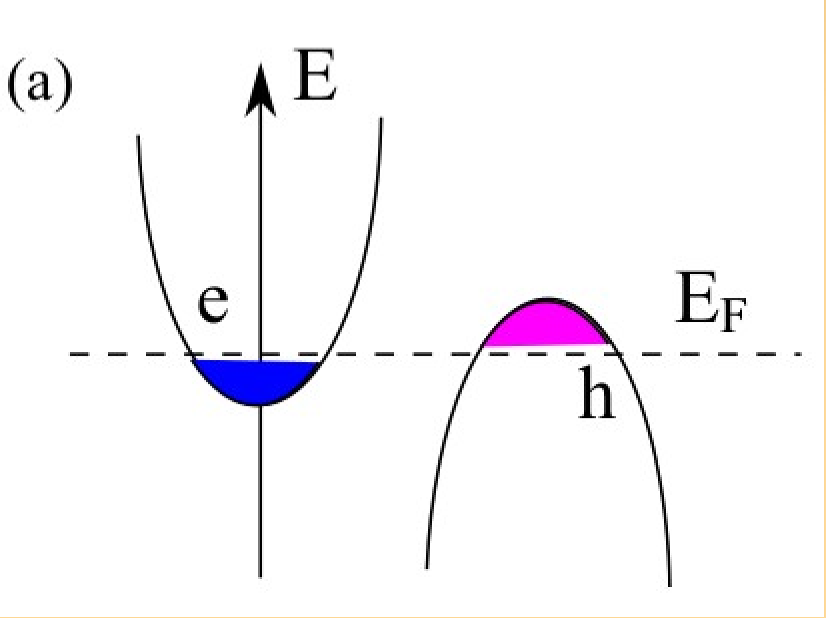
Зеркальное Андреевское отражение

на границе между сверхпроводником и двумерным полуметаллом

Полуметалл

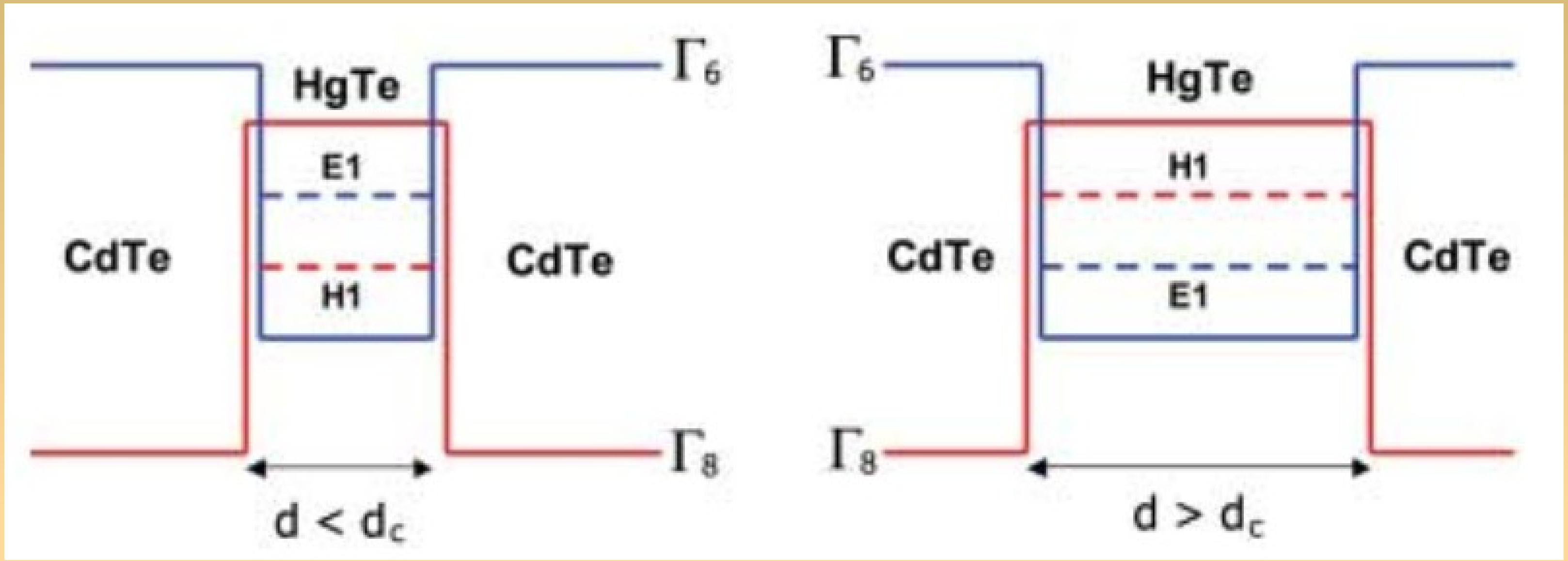
limit $\varepsilon_F < \Delta$ - ???



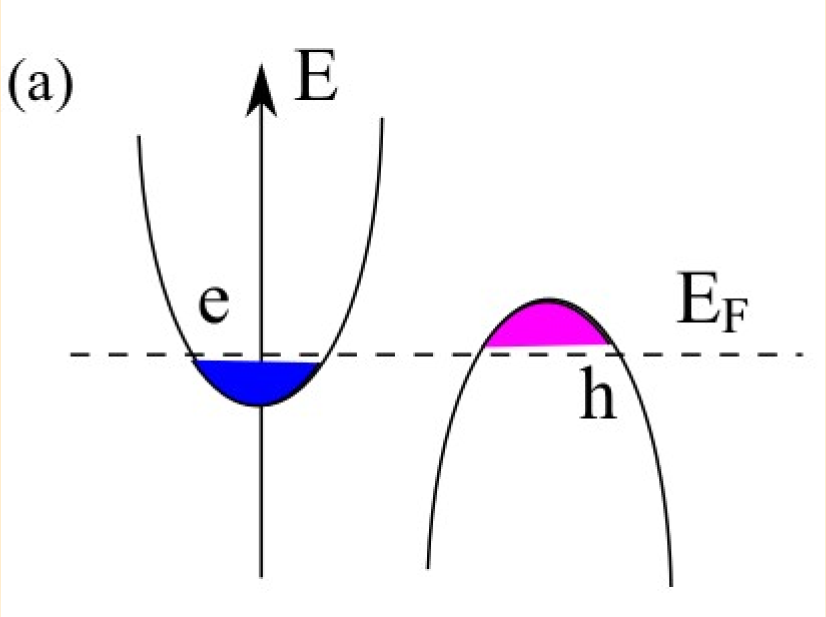


Дж. Займан, Принципы теории твердого тела, учебник

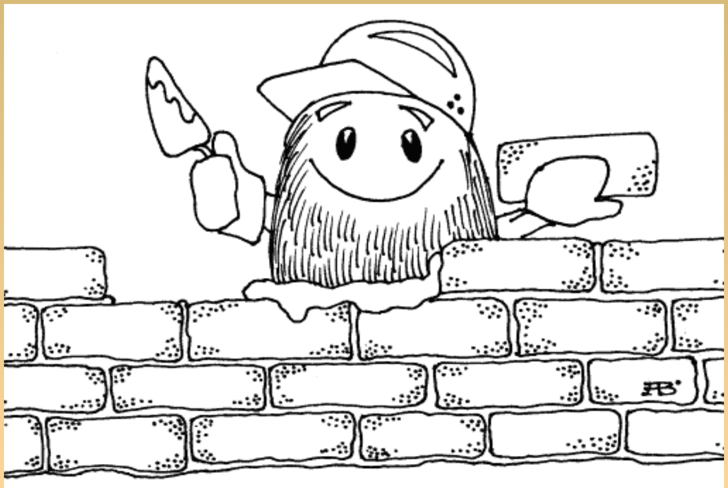
Narrow HgTe quantum wells
Quantum spin Hall effect

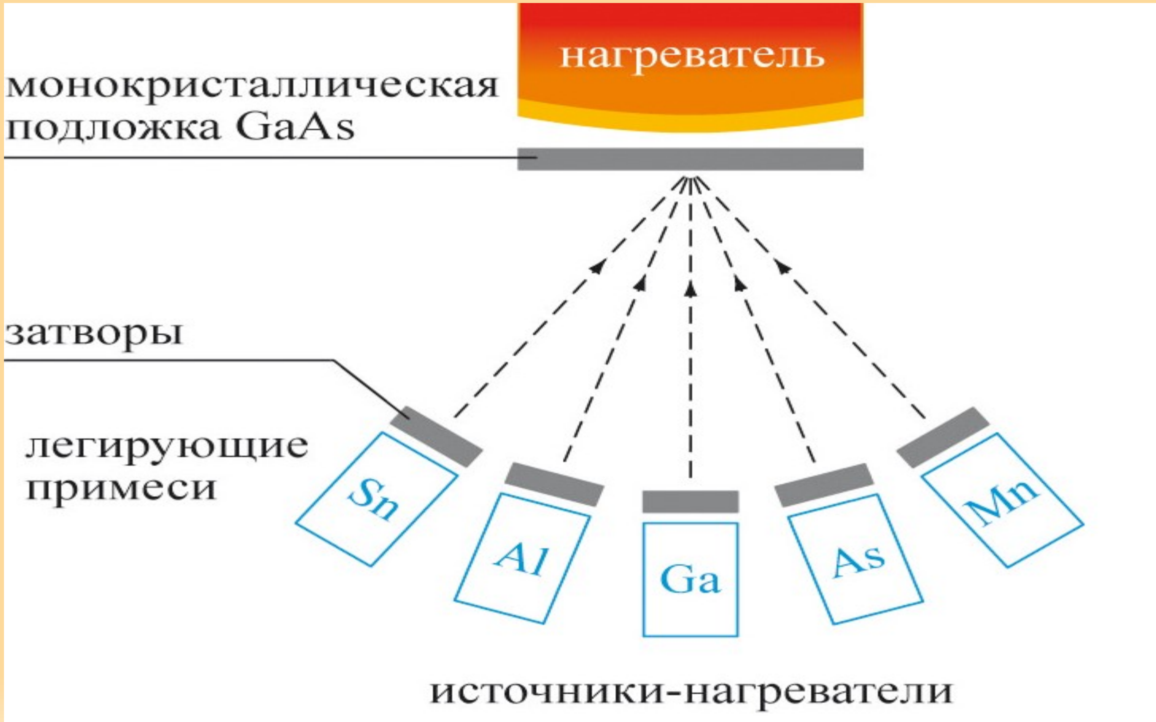


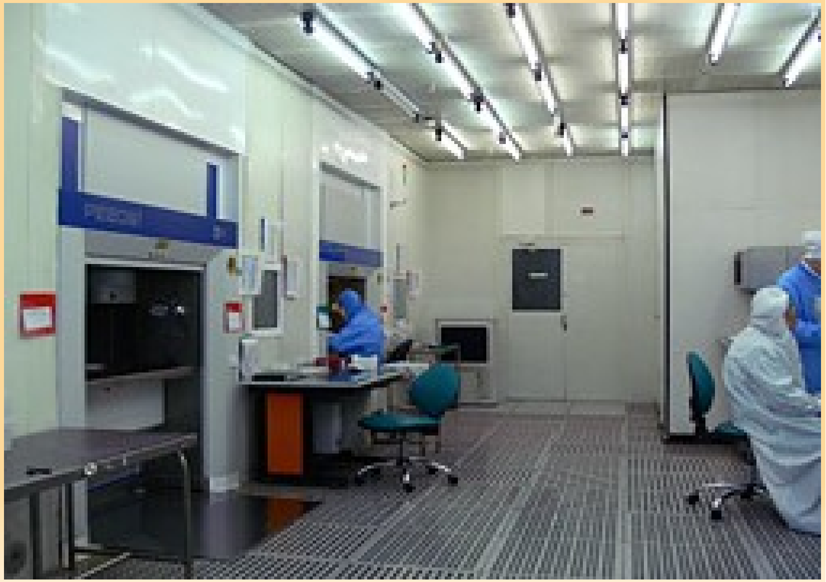
B. A. Bernevig, S.-C. Zhang,
Phys. Rev. Lett. 96, 106802 (2006)



Изготовление структур с квантовыми ямами

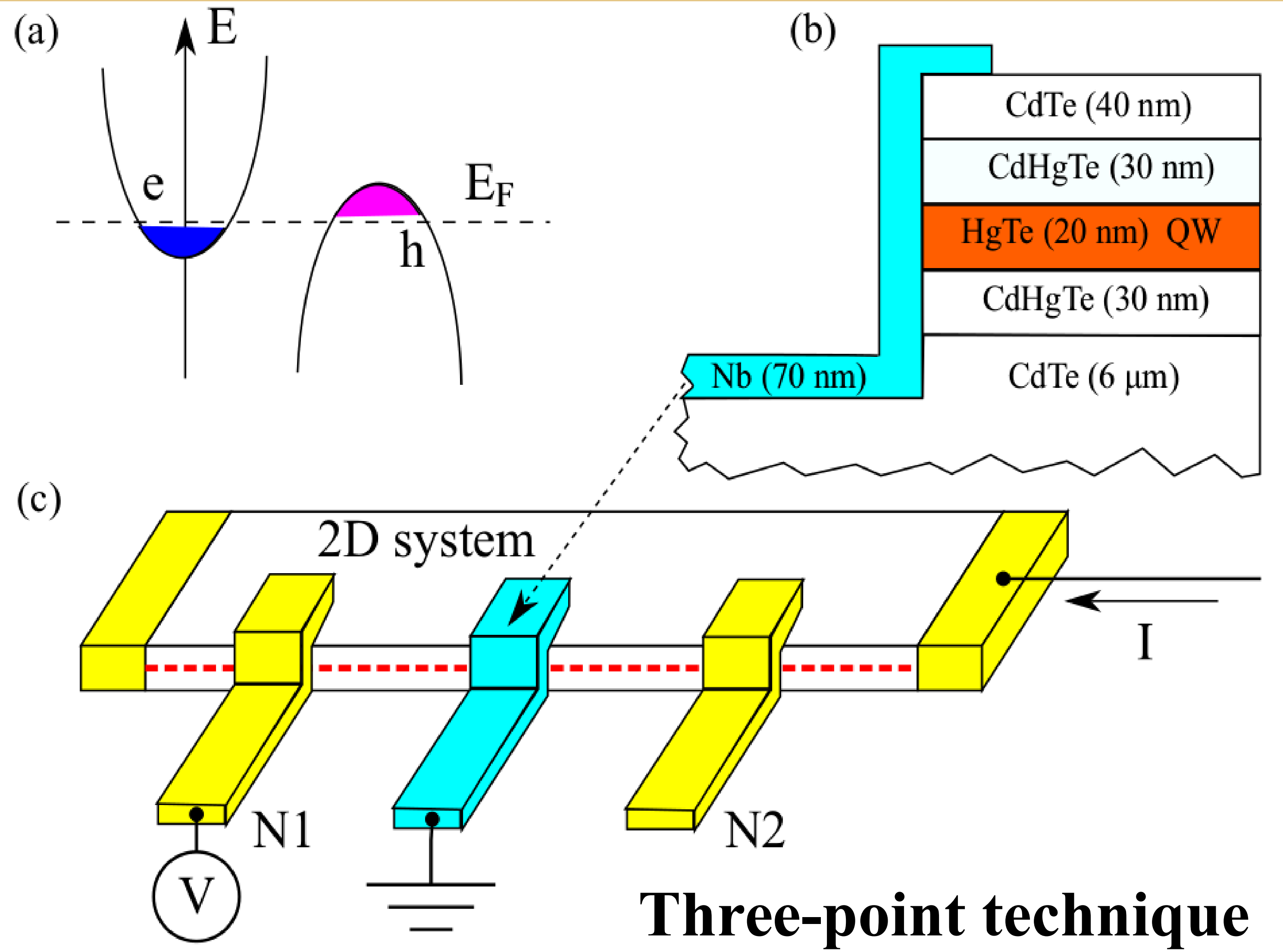






Single S side contact to a 2D semimetal
Phys. Rev. B 93, 041303(R) (2016)

wide (d=20 nm) HgTe quantum well

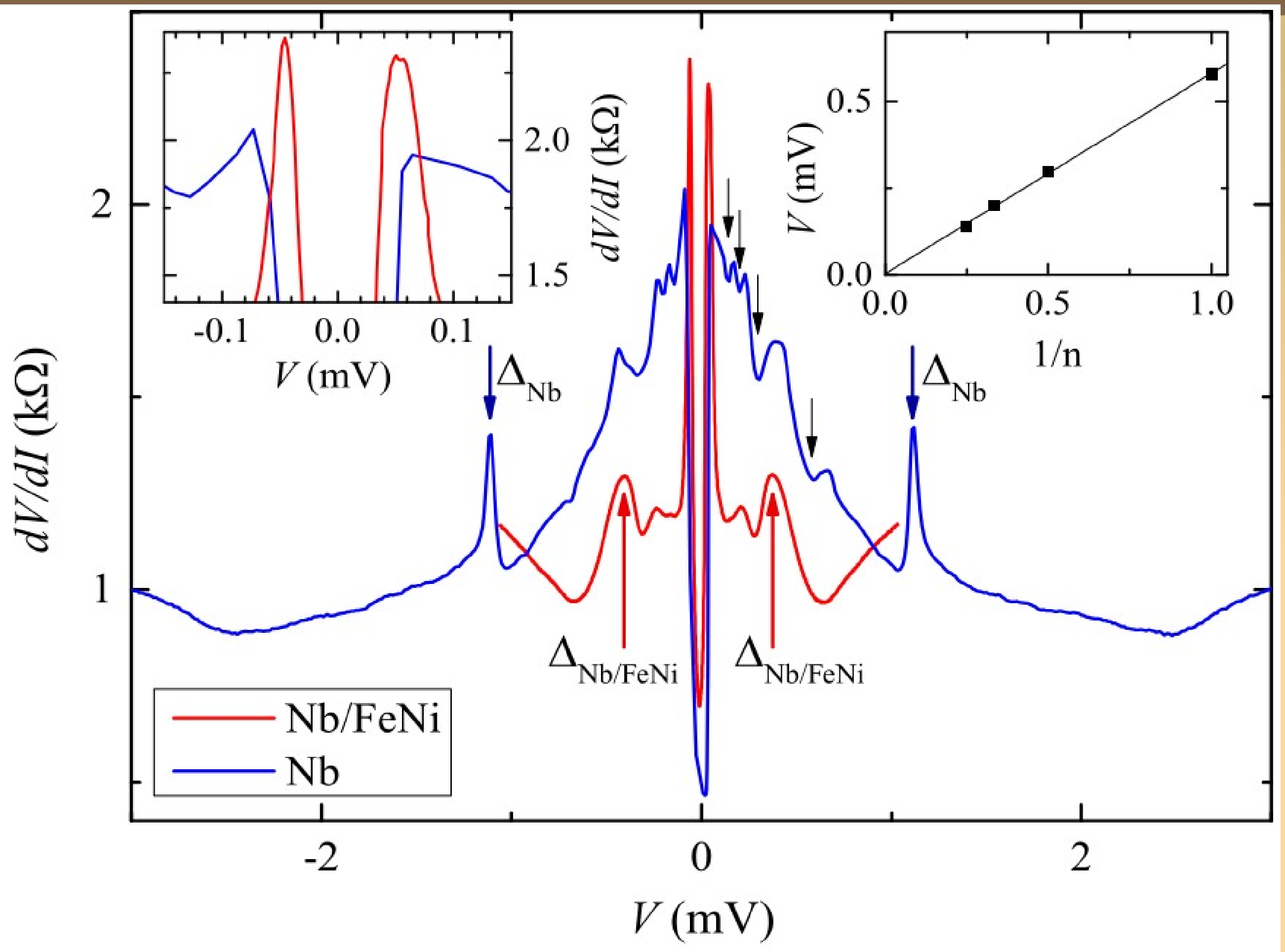


Three-point technique

(e: 4×10^5 cm^2 /V s at 0.5×10^{11} cm^{-2})

(h: 5×10^4 cm^2 /V s at 1×10^{11} cm^{-2})

dV/dI(V) curves for a single SN interface



Well developed Andreev curve:

(i) Every curve demonstrates a clearly defined superconducting gap (± 1.15 mV, which is in good correspondence with the expected 9K);

(ii) the subgap resistance is undoubtedly finite, which is only possible due to Andreev reflection

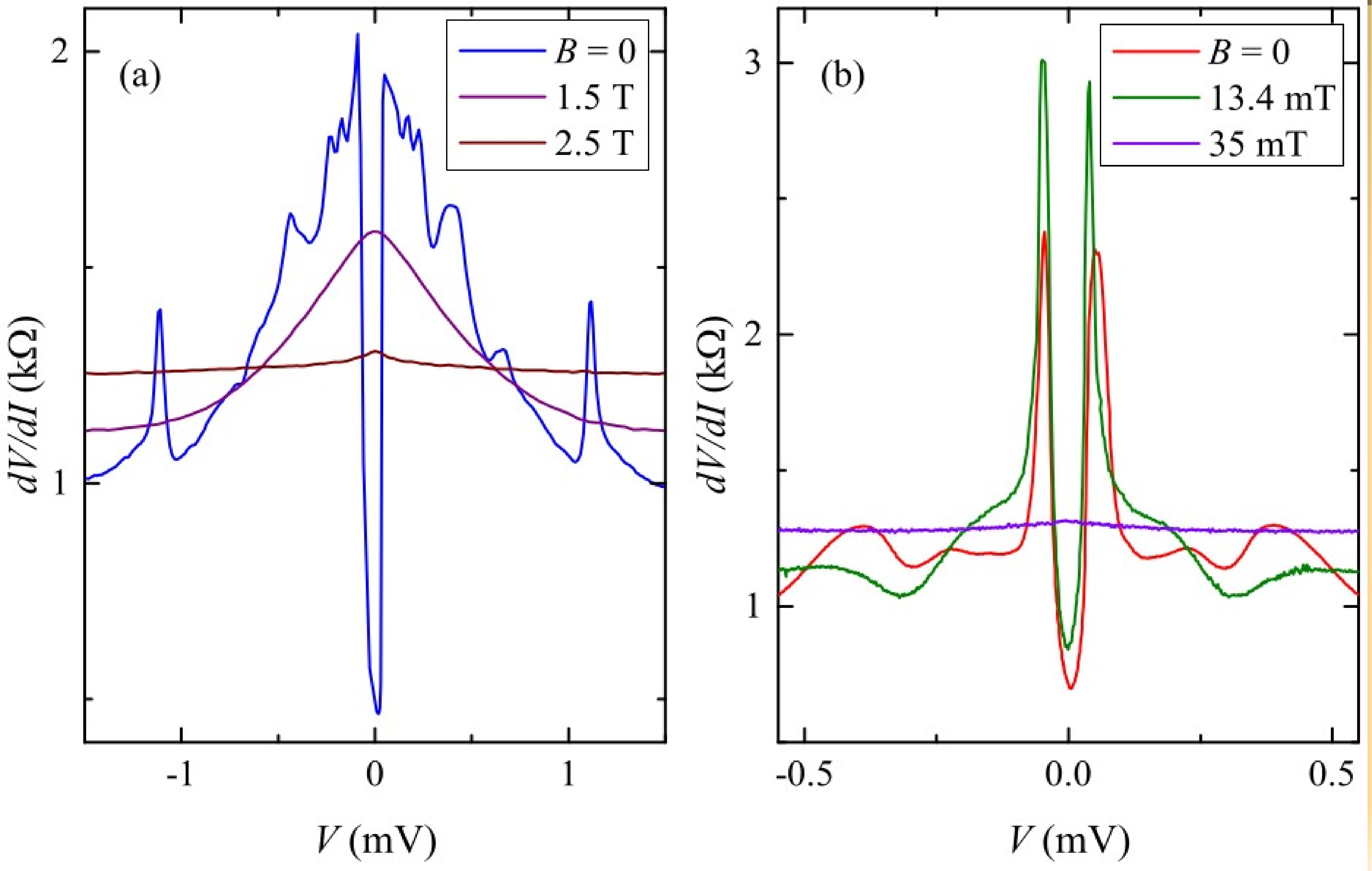
(T=0.5 => Z=1 (T= 1 / (1 + Z^2)) (BTK)

The specifics of this experiment:

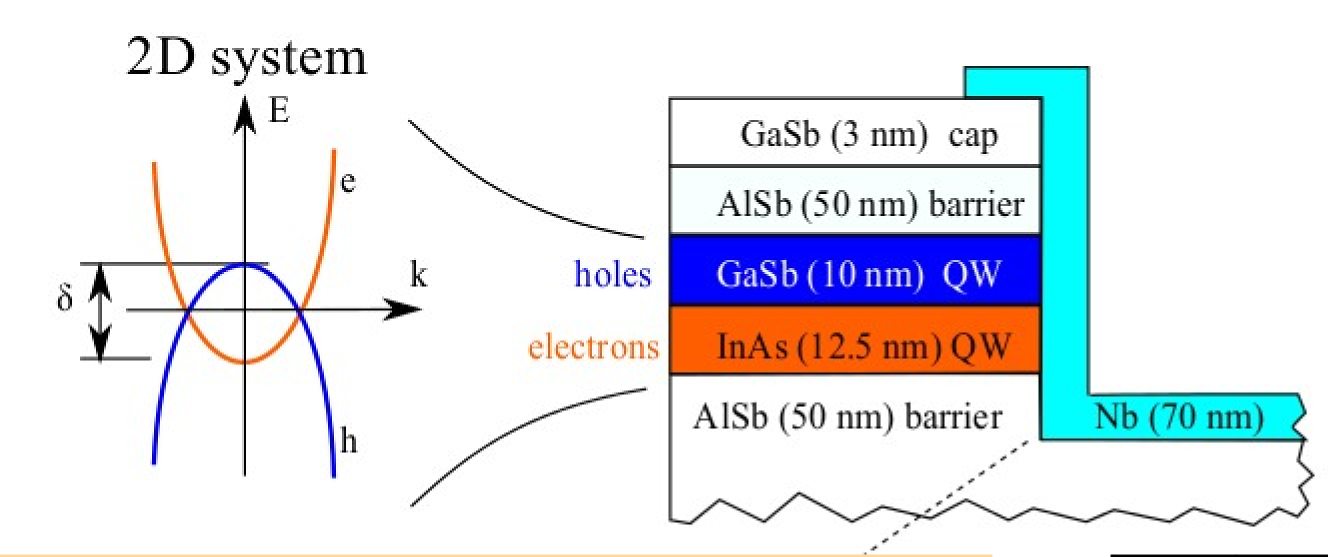
(i) Strong, twice below R_N , zero-bias differential resistance drop.

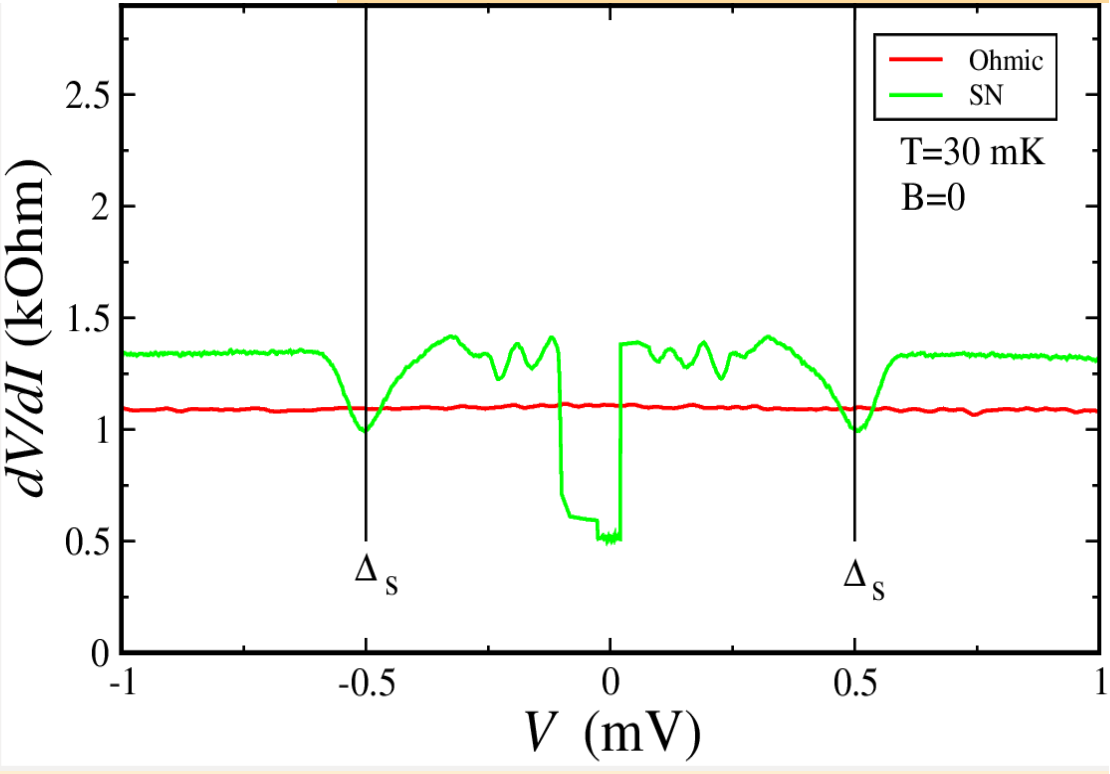
(ii) The shallow subgap resistance oscillations with 1/n periodicity

dV/dI(V) curves: in-plane magnetic field dependence



dV/dI(V) curves for another semimetal (InAs/GaSb double quantum well)





Semimetal-specific effects?

The results are <u>independent of the superconducting material.</u>

Similar results are obtained <u>for different 2D semimetals.</u>

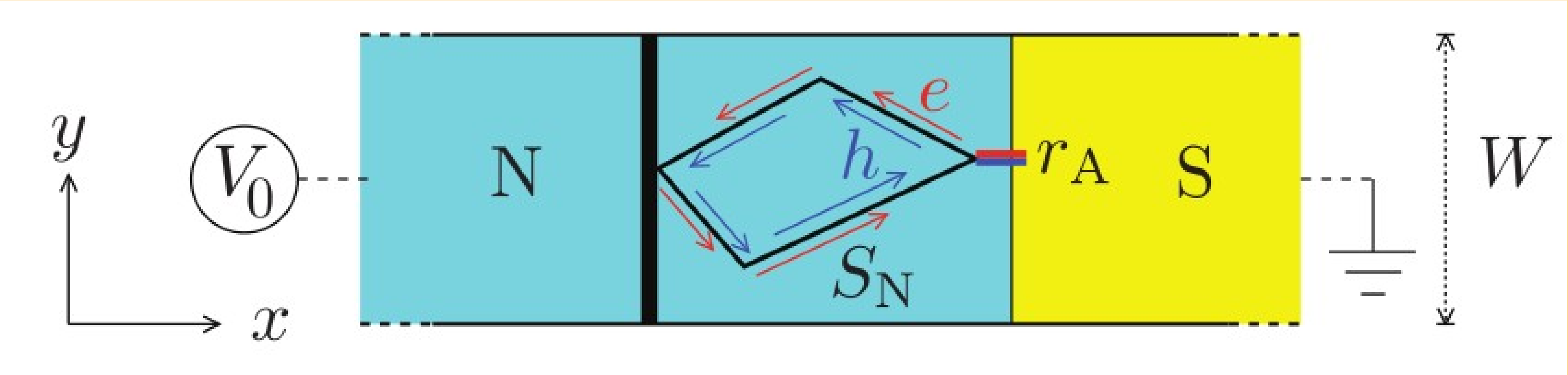
Should they be regarded as specific to a 2D semimetal in proximity with a superconductor?

Effect of disorder?

We cannot connect these effects with trivial disorder:

it can only provide a small, weak antilocalization-like correction at zero bias, known as disorder-enhanced Andreev reflection (I. K. Marmorkos, C. W. J. Beenakker, and R. A. Jalabert, Phys. Rev. B 48, 2811 (1993); D. I. Pikulin, J. P. Dahlhaus, M. Wimmer, H. Schomerus, and C. W. J. Beenakker, New J. Phys. 14, 125011 (2012).).

In contrast, zero-bias resistance drops twice below the normal value in our experiment.

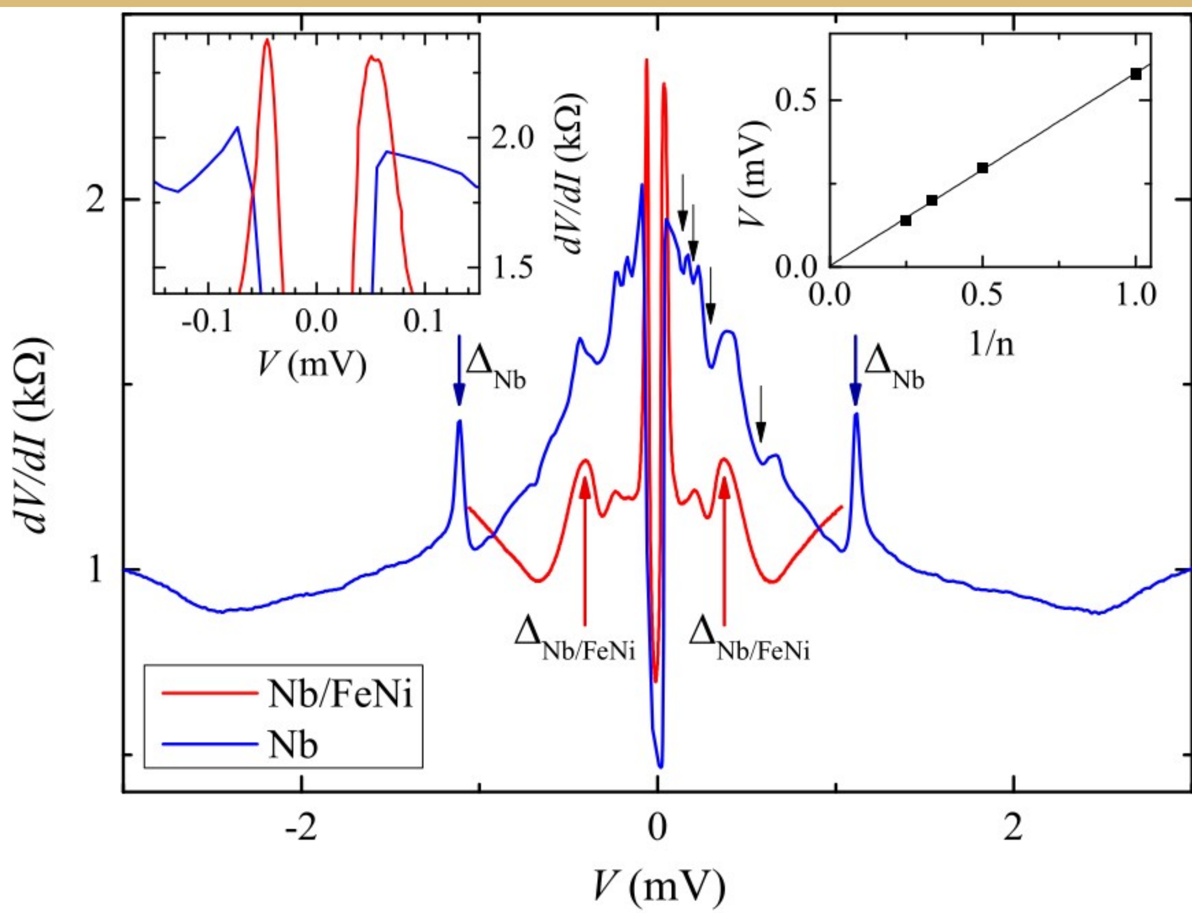


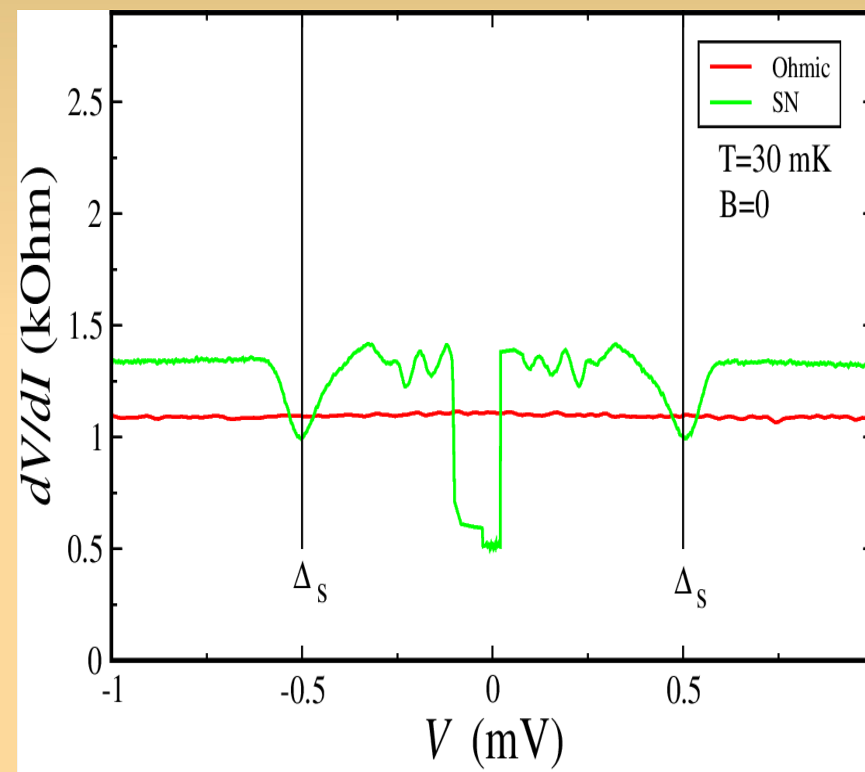
Moreover, trivial backscattering cannot provide subsequent energy increase in multiple reflections, which is responsible for the 1/n periodicity:

MAR (Multiple Andreev reflection) in SNS structures

$E_n = 2\Delta_{NbN}/n$, n = 1, 2, 3...)

dV/dI(V) zero-bias anomaly – different regimes of Andreev reflection





Zero-bias region – RAR.
Its **width** is defined by the band overlap => it is independent of the particular superconductor material.

Outside it – SAR.
The oscillations are present in SAR regime.

Что дальше?

Topological semimetals

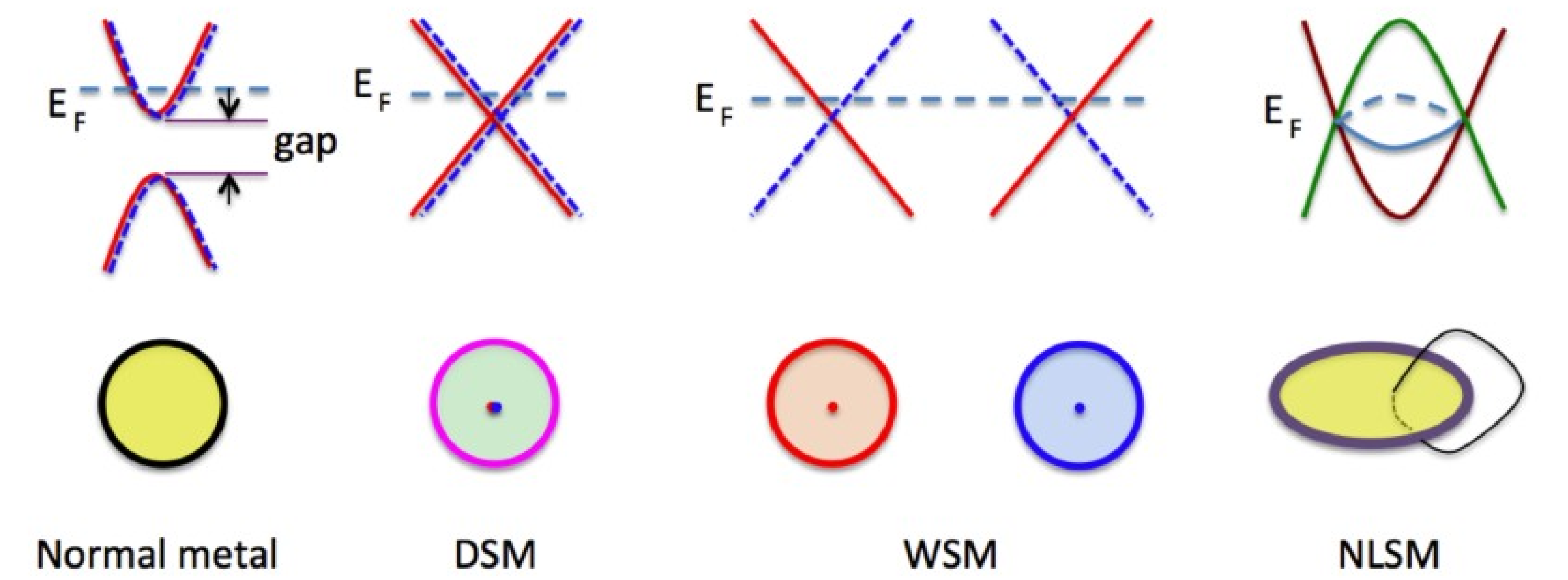


FIG. 1: (Color online) Schematic band structure and Fermi surface (with Fermi level shift slightly off the nodal points) for normal metal and three kinds of topological semimetals, Dirac semimetal (DSM), Weyl semimetal (WSM) and Node-Line Semimetal (NLSM). The close path (black thin circle) interlocked with the nodal ring (thick circle) is also shown.

Topological Semimetals Predicted from First-principles Calculations Hongming Weng, Xi Dai, and Zhong Fang arXiv:1603.04744

Topological semimetals

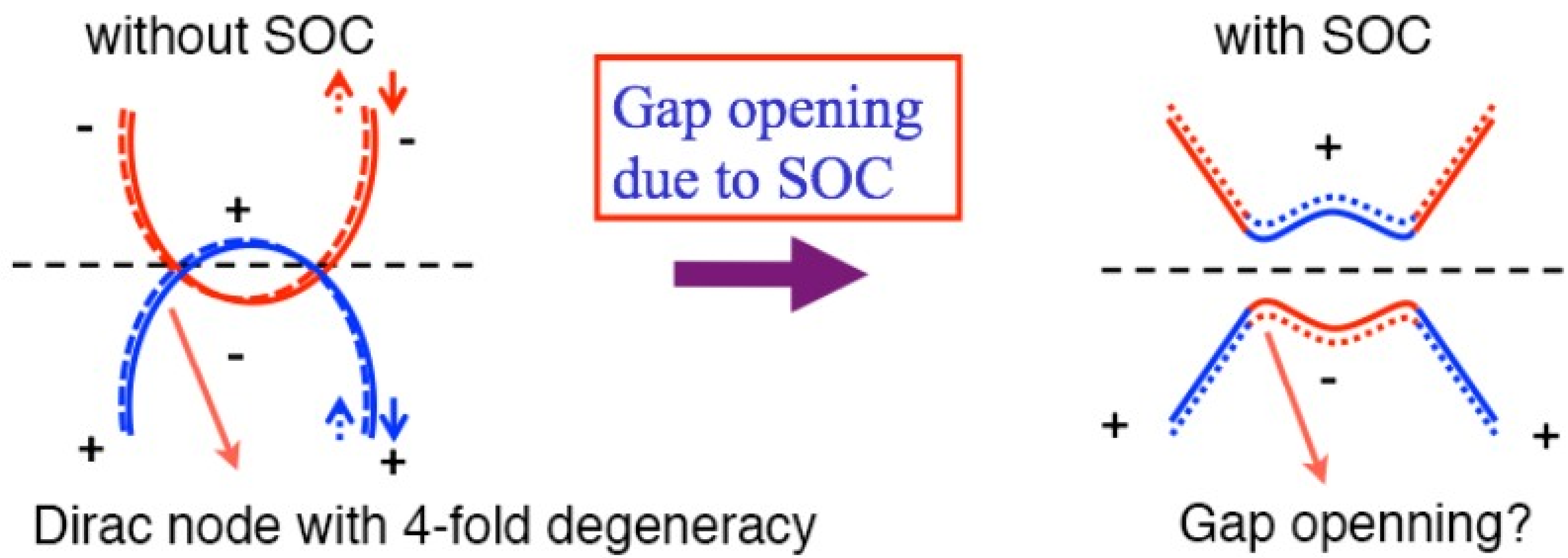


FIG. 2: (Color online) Schematic plot of band inversion mechanism. (left) The case without SOC, band inversion between two spin degenerate (dashed line for up spin, solid one for down spin) bands. + and - indicates the parity of the states at time-reversal invariant moment. (right) After including SOC, the band crossings are lifted and band gap is open.

Topological Semimetals Predicted from First-principles Calculations Hongming Weng, Xi Dai, and Zhong Fang arXiv:1603.04744

Благодарности

Measurements

A. Kononov, E.V. Deviatov

ISSP RAS Chernogolovka Russia

Samples

S.V. Egorov *ISSP RAS Chernogolovka Russia*

Z. D. Kvon, S. A. Dvoretsky, N. N. Mikhailov

B.R. Semyagin, V.V. Preobrazhenskii, M.A. Putyato, E.A. Emelyanov

Institute of Semiconductor Physics, Novosibirsk Russia

Discussions

Ya. Fominov, A.M. Bobkov, I.V. Bobkova,

V.T. Dolgopolov, T.M. Klapwijk