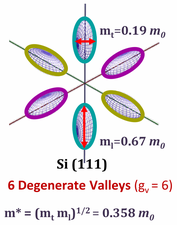
Valley Degeneracy and Valley Drag on Si(111) Surfaces

Robert McFarland*, Tomasz Kott, Binhui Hu, Bruce Kane *Laboratory for Physical Sciences, University of Maryland, College Park*
Luyan Sun, *Department of Applied Physics, Yale University*

Introduction

The 111 surface of silicon is predicted to retain the sixfold valley degeneracy of the ideal bulk crystal. We have developed a method for fabricating field effect transistors using vacuum as a dielectric in order to study electron transport on the bare H-terminated surface, free from the complications created by intrinsic disorder at Si-SiO_2 interfaces. The resulting devices display very high mobilities (up to 110,000 cm^2/Vs at 70 mK, more than twice as large as the best silicon MOSFETs), enabling us to probe valley-dependent transport dynamics to a much greater degree than previously possible.

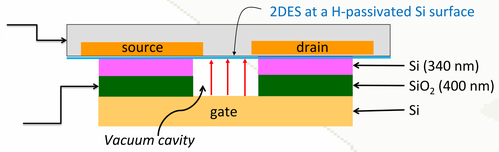


H-Si(111) Vacuum FET

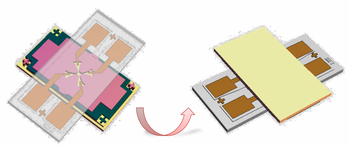
The H-Si(111) FET is made from two separate Si substrates, each with a distinct function:

1. H-Si (111) substrate:
16mm x 7mm, p-type, FZ
(ρ ~10 kΩ cm, <0.2° miscut)
P implanted contacts

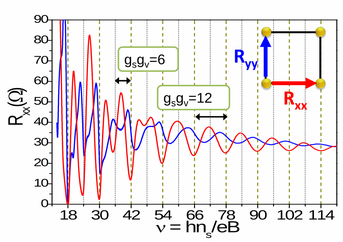
2. SOI ("remote gate"):
7mm x 10mm
B implanted gate & shield



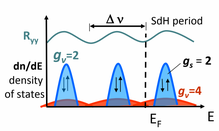
The two substrates are cleaned and bonded together in vacuum via van der Waals forces. The bonding protects the H-Si(111) surface inside a vacuum cavity and allows gate to induce a 2DES on the H-Si(111) surface within the cavity region.



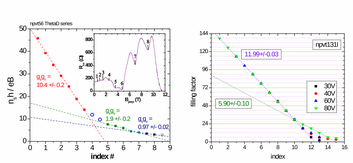
Measuring Degeneracy

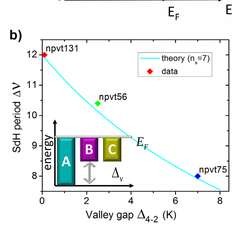


Low field Shubnikov-de Hass (SdH) oscillations reveal a clearly six-fold degenerate system with emerging anisotropic behavior.



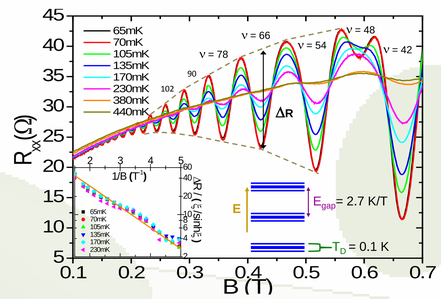
Other devices display a strong zero field valley splitting. The two-fold states tend to dominate the SdH signal, even though all six valleys are occupied.



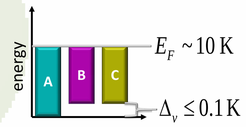


Valley Splitting

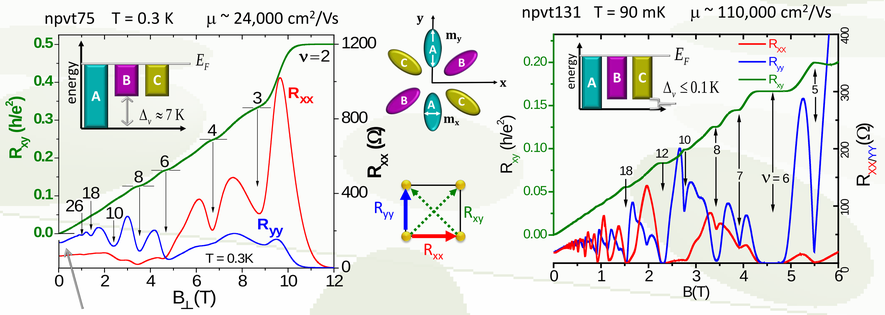
We can divide valley splitting into two rough groups: **Intrinsic** and ***B*-dependent**. To measure the former, we use low *B* SdH oscillations.



The temperature dependence of the SdH oscillations gives the level broadening Γ, an *upper bound* on the intrinsic splitting.



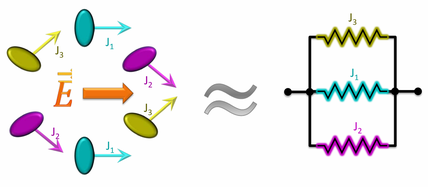
At large B fields, the valley degeneracy lifts completely, revealing minima spaced by Δν=1; this behavior occurs in all devices measured.



The strong zero field valley splitting results in anisotropy ($\rho_{xx} \neq \rho_{yy}$) at B = 0.

Valley Effects

For ***B* = 0** ρ_{xx} & ρ_{xy} are both suppressed due to parallel transport in anisotropic valleys.



$$\bar{m} = \frac{m_x + m_y}{2} \rightarrow m_{op} = \left(\frac{m_x^{-1} + m_y^{-1}}{2}\right)^{-1}$$

$$\rho_{xx} \rightarrow \left(\frac{\bar{m}}{n_s e^2 \tau}\right)\frac{m^{*2}}{\bar{m}^2} \qquad \rho_{yx} \rightarrow \left(\frac{B}{n_s e}\right)\frac{m^{*2}}{\bar{m}^2}$$

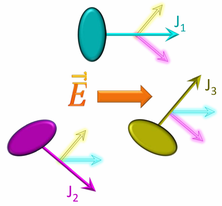
$$\frac{m^{*2}}{\bar{m}^2} = \frac{m_{op}}{\bar{m}} \approx 0.687$$

We can use this correction to probe interactions between valleys.

Valley Drag

As the simplest valley-valley interaction, we allow the current in each valley to "tug" the currents in the other valleys, similar to Coulomb drag.

- Friction between valley currents
  - long-range interaction
  - conserves 2DES momentum
- NOT inter-valley scattering
  - short-range interaction
  - lattice-mediated



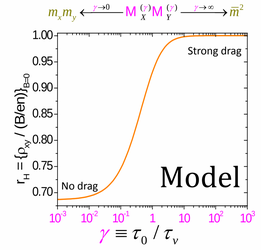
Drude Model — drag term

$$\frac{M_j \mathbf{v}_j}{\tau_0} = e(\mathbf{E} + \mathbf{v}_j \times \mathbf{B}) + \frac{1}{\tau_v}\sum_{k \neq j}\left(M_{jk}(\mathbf{v}_k - \mathbf{v}_j)\right)$$

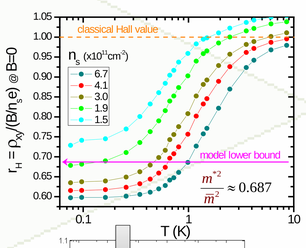
j, k range over valleys — relative momenta $M_{jk}^{-1} = M_j^{-1} + M_k^{-1}$

$$r_H = \left(\frac{\rho_{yx}}{B/n_s e}\right)_{B\to 0} = \frac{M_x^{(\gamma)} M_y^{(\gamma)}}{\bar{m}^2}$$

$$m_x m_y \xleftarrow{\gamma\to 0} M_x^{(\gamma)} M_y^{(\gamma)} \xrightarrow{\gamma\to\infty} \bar{m}^2$$

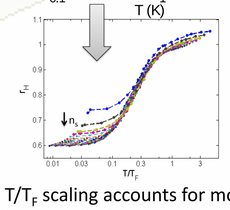


Drag Data

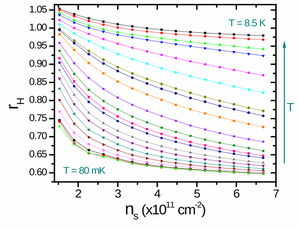


Low T r_H *below* lower bound

- Known Hall corrections should ***increase*** r_H, not decrease it.



T/T_F scaling accounts for most but not all of T dependence.



Summary

- Vacuum bonding creates very high quality devices & uncovers new physics.
- Sixfold degeneracy indeed preserved in {111} planes
- The large valley state space affects transport in many ways
- Zero-field Hall suppression provides a powerful new means to probe valley-valley interaction.

For more information…

- *Phys. Rev. B 80, 161310(R) (2009)*
- *Phys. Rev. Lett. 99, 016801 (2007)*
- *Appl. Phys. Lett 87 052106 (2005)*

* robertnm@mailaps.org