Resolving Superconducting Vortices in Pb Monolayer and Thin Films on Si(111)

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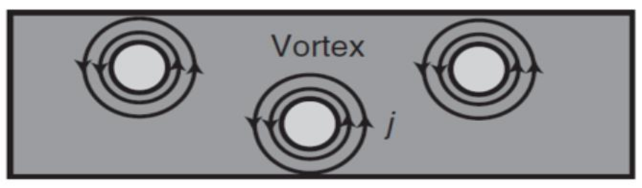
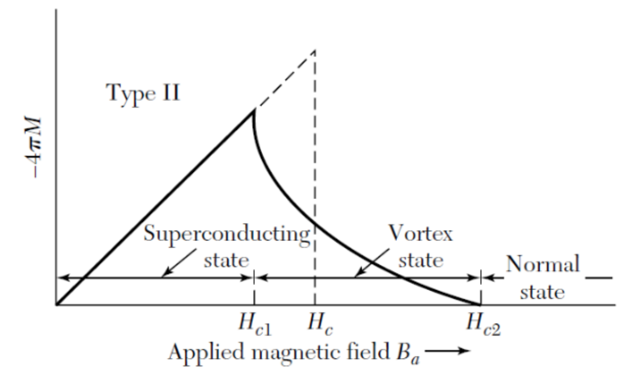
Introduction

Superconducting Vortex



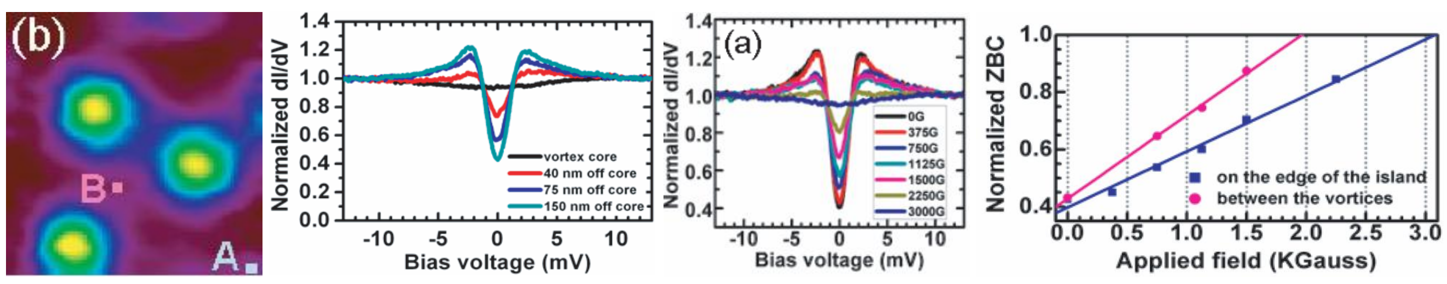


- Applied magnetic field between H_{c1} and H_{c2} magnetic flux enters sample in quantized form.

$$\Phi_0 = \frac{hc}{2e} \approx 2.07 \times 10^{-15}\ (T * m^2)$$

- The superconducting vortices prevent the magnetic field from driving the rest of the sample into the non-superconducting state.

Literature Review: 2D Pb island on Si(111)

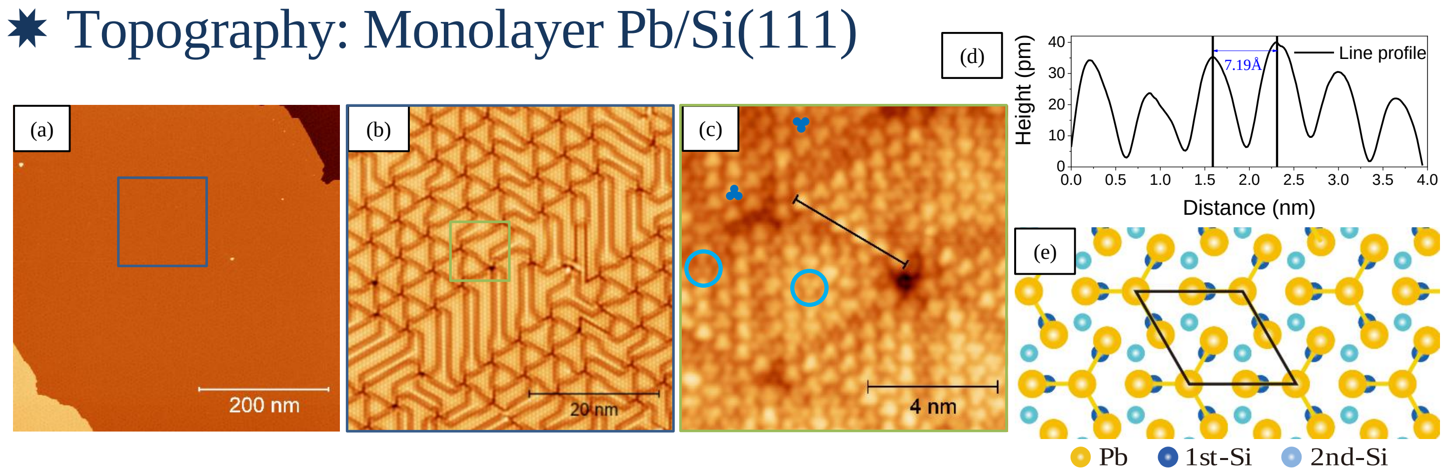


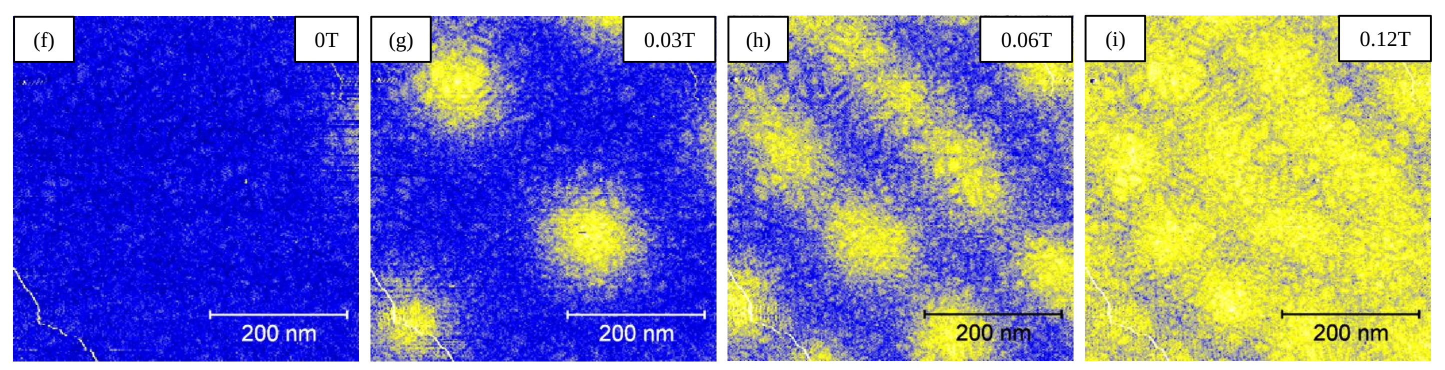
Ning, Y. X. *et al. Europhysics Letters (EPL)* **85**, 27004 (2009).

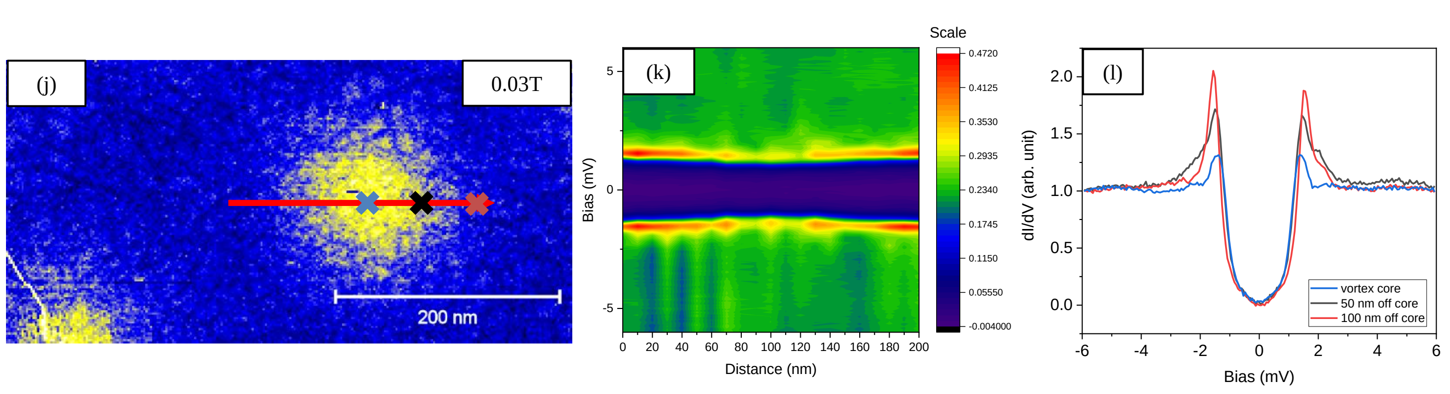
- When the magnetic field increases, the vortex density rises and superconducting gap correspondingly decreases.

Experimental Results

Topography: Monolayer Pb/Si(111)

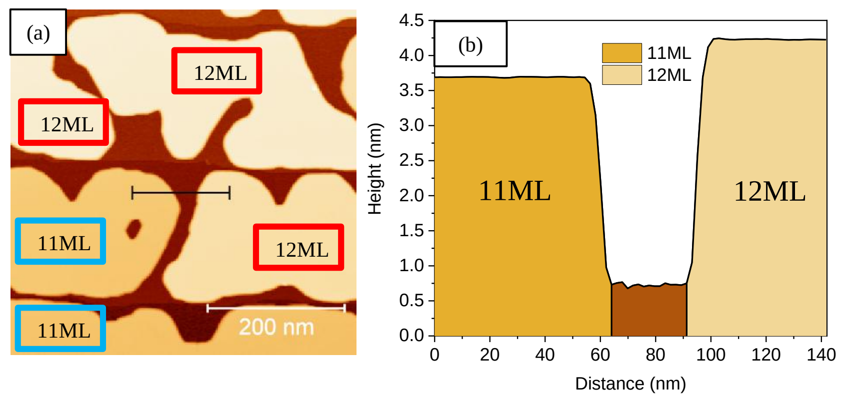




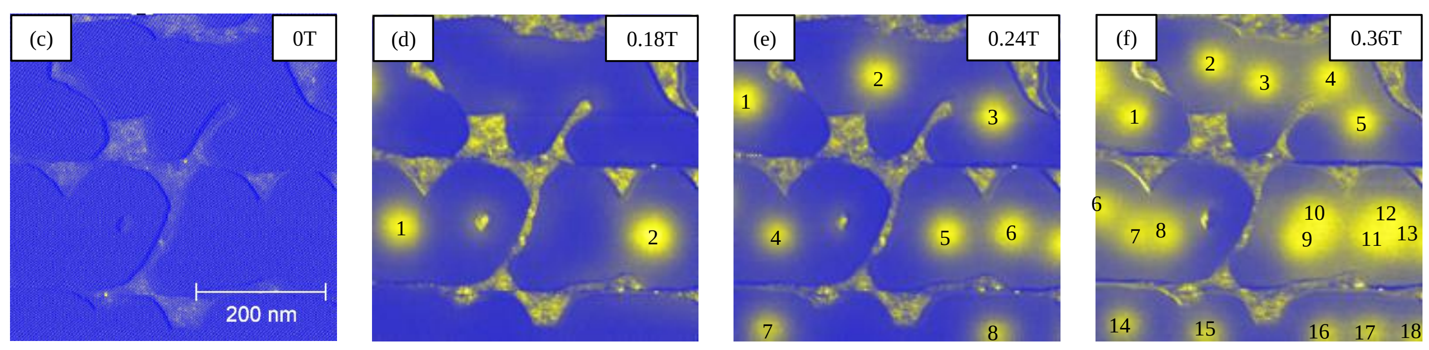


- Fig.(a)~(c), we zoom in Pb/Si(111)-SIC phase and observe the lattice constant is 7.2 ± 0.5Å.
- As the magnetic field increases, the number of vortices increases, leading to a reduction in the vortex lattice constant d.
- Fig.(l), To remove the remaining superconducting gap at the vortex center, caused by a SC tip, a deconvolution process has been performed.
- The atomic-resolution image shows domains featuring upward- or downward-pointing triangles, within which four Pb atoms can be clearly identified forming the $\sqrt{3} \times \sqrt{3}$ SIC structure.

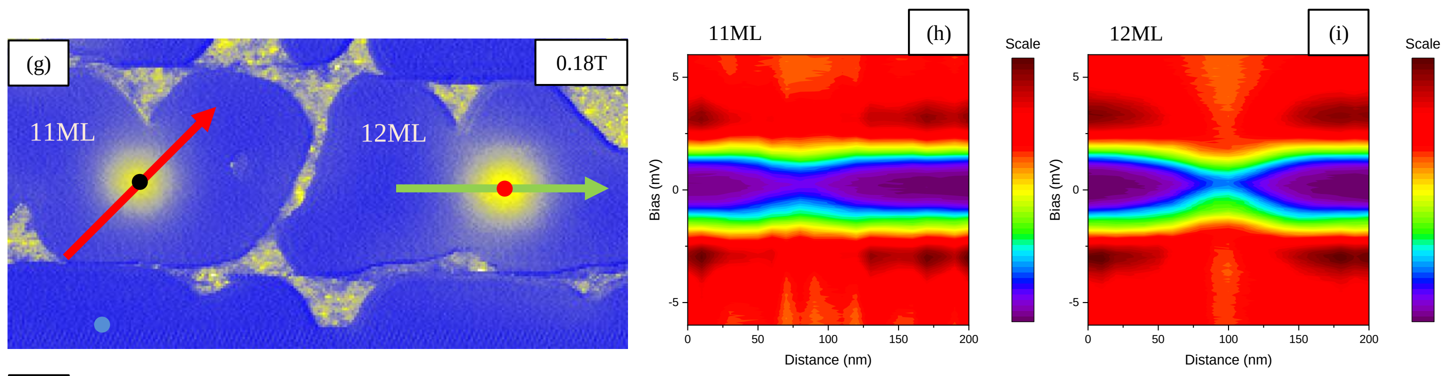
Topography: Pb 2D Island on Si(111)

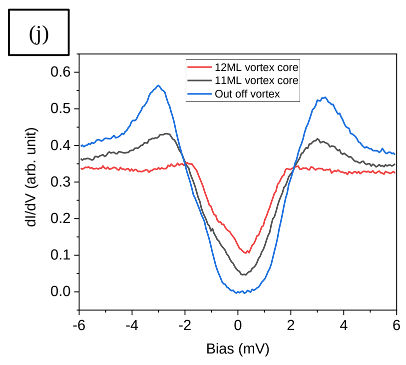


- Fig.(a), we observe different thickness islands. One with height 3.05nm, another is 3.51nm
- Here, 1 ML is defined as the interlayer spacing of Pb(111), which is 0.286 nm.



- The zero-bias conductance at the vortex core increases with the thickness of the Pb nano-islands due to the increased normal state conductance.





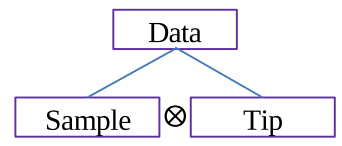
- The larger vortex size in the 12ML island indicates a longer coherence length (ξ_{GL}) and a smaller critical field (H_{c2}) compared with the 11-ML island.
- The superconducting gap at the vortex center is larger in 11 ML, whereas the zero-bias conductance is higher in 12 ML.

Theoretical Calculations

Deconvolution method

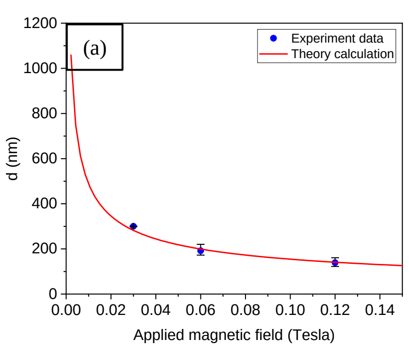
$$\sigma(r,0,T) = \sigma_0(T) + (1-\sigma_0(T)) \times \left(1 - \tanh\left(\frac{|r|}{\sqrt{2}\cdot \xi_{GL}(T)}\right)\right)$$

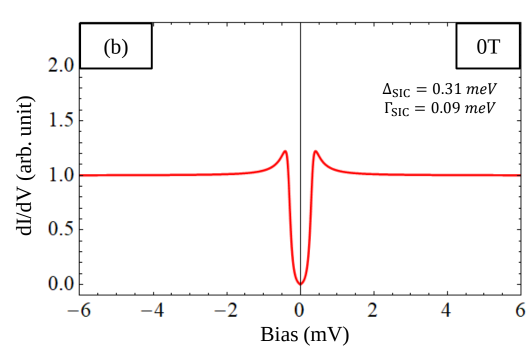
- $\Delta_{SIC} = 0.31\ meV$; $\Delta_{Island} \approx \Delta_{Pb}$
- BCS fitting result
- To get Δ_{Tip}

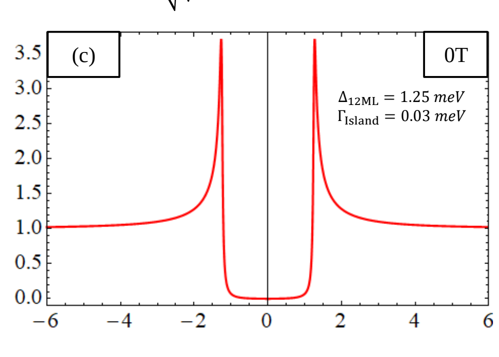


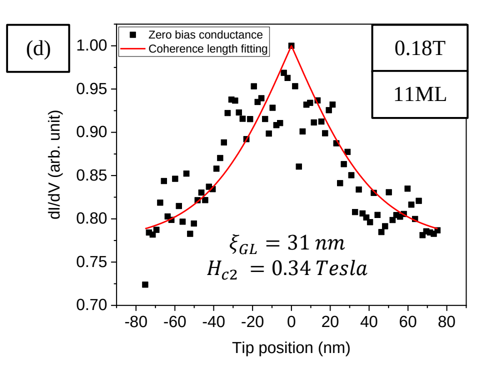
$$H_{c2}(T) = \frac{\Phi_0}{2\pi \cdot \xi_{GL}^2(T)},\ \Phi_0 \approx 2.07 \times 10^{-15}\ (T * m^2)$$

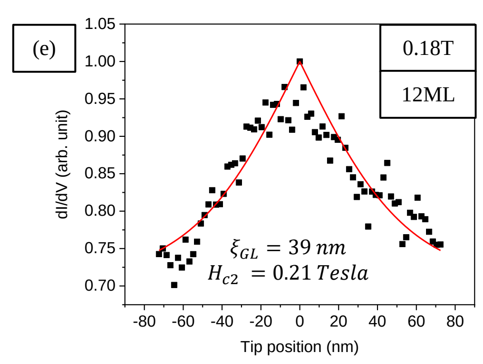
$$d = \sqrt{\frac{2\Phi_0}{\sqrt{3}H}}$$

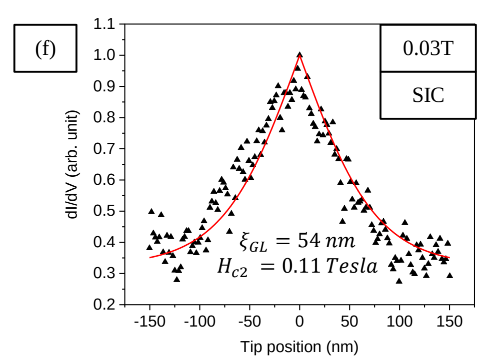












- Using the deconvolution method, we find that as the number of monolayers increases, Δ increase and while the broadening parameter Γ decreases, likely because boundary effects become weaker in thicker films.
- From above plot, monolayer-SIC has the largest coherence length ξ_{GL} and smallest H_{c2}.
- The experimentally fitted value of the magnetic flux quantum is $\Phi_0 = 2.34 \times 10^{-15}\ (T * m^2)$, which differs from the theoretical value by 1.73%.

Summary

1. We successfully fabricated Pb/Si(111) - SIC phase and also observed the SC vortices carrying a single magnetic flux quantum Φ_0, with the vortex lattice structure following Abrikosov's theoretical prediction.
2. We estimated the upper critical field (H_{c2}) using Ginzburg–Landau theory, which is consistent with our results and those reported in previous studies.
3. In 2D monolayer islands, the zero-bias conductance at the vortex core is higher in even-numbered layers than in odd-numbered layers.

Reference

1. *Ning, Y. X. et al. Observation of surface superconductivity and direct vortex imaging of a Pb thin island with a scanning tunneling microscope. Europhysics Letters (EPL)* ***85****, 27004 (2009).*
2. *Guo Y, Zhang YF, Bao XY, Han TZ, Tang Z, Zhang LX, Zhu WG, Wang EG, Niu Q, Qiu ZQ, Jia JF, Zhao ZX, Xue QK. Superconductivity modulated by quantum size effects. Science. 2004 Dec 10;306(5703):1915-7. doi: 10.1126/science.1105130. PMID: 15591197.*
3. *Zhang, T., Cheng, P., Li, WJ. et al. Superconductivity in one-atomic-layer metal films grown on Si(111). Nature Phys 6, 104–108 (2010).*