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Flux pinning by InAs nanorods in Nb thin films

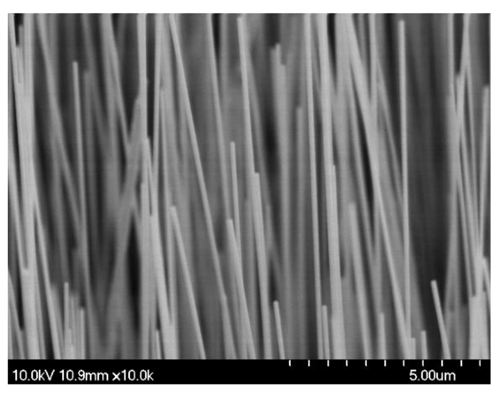
DongHo Kim, TaeJong Hwang, Minhyuck Jo, JaeChul Shin: Yeungnam University, S. Korea

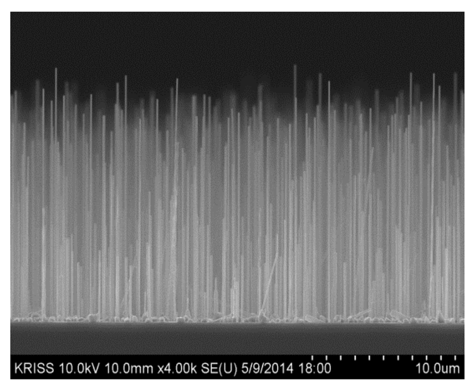
Motivation

- Linear defects are excellent flux pinning centers
- Semiconductor nanorods with their diameters comparable to the superconducting coherence lengths are routinely grown by MOCVD
- Why not semiconducting linear defects for flux pinning?

Growth of InAs nanorods

- Horizontal MOCVD system
- Source: Arsine (AsH_3) and trimethyl-indium (TMIn)
- Substrate: p-type Si (111)
- Growth temperature: 570 °C



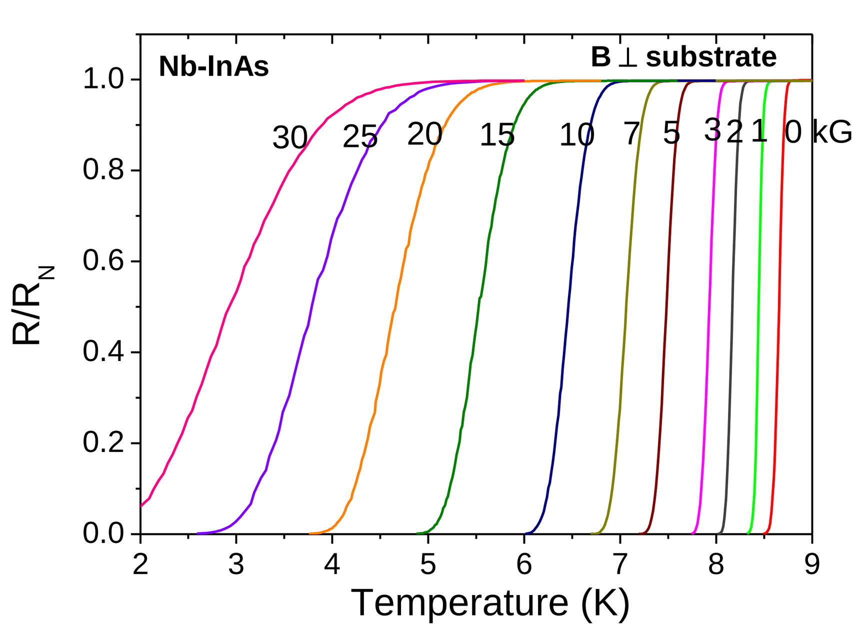


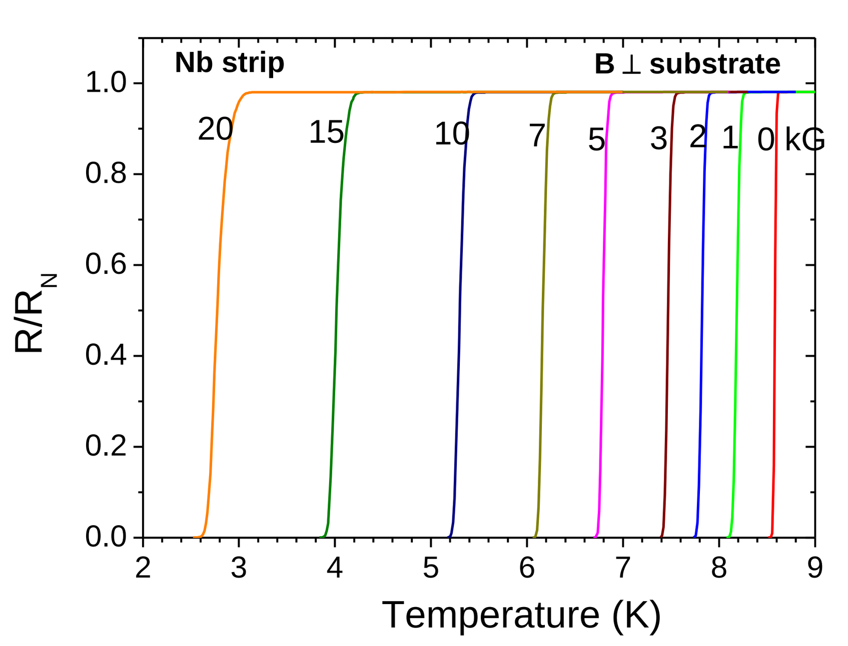
- Mostly vertical growth
- Some nanorods grow in oblique direction
- Non-uniform areal density: ~2×10^9/cm²
- Matching field B_Φ : $\Phi_0\times$ (density) = ~0.04 T
- Nanorod length: 5 μm ± 2 μm
- Nanorod diameter d: 80 nm ± 5 nm

Nb deposition

- DC magnetron sputtering
  Ar pressure: 5×10^{-3} mbar
  Power: 145 W
  Deposition rate: 28 nm/min
- Formation of Nb strip using metal shadow mask
- Nb thicknesses t: 400 nm
- Two samples: **Nb-InAs** (on nanorod grown substrate)
  Nb (on bare substrate)

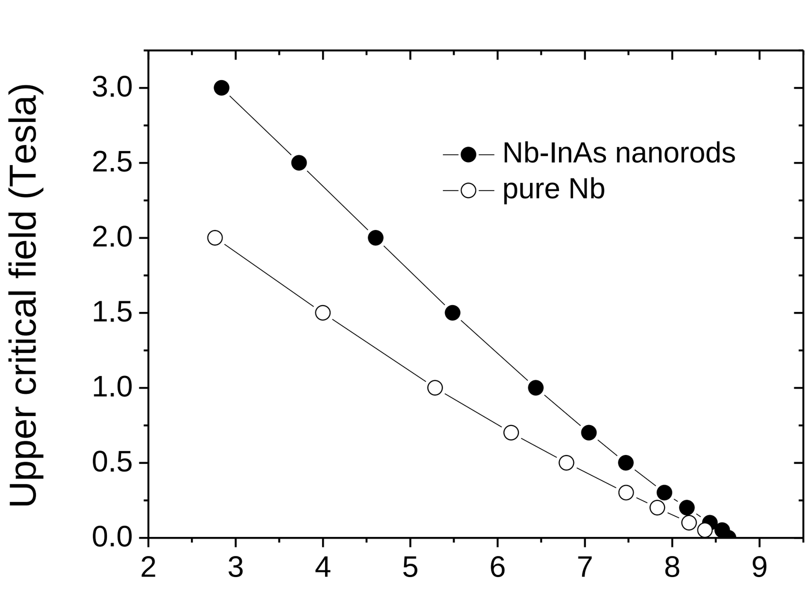
Resistive transitions for field ⊥ substrate





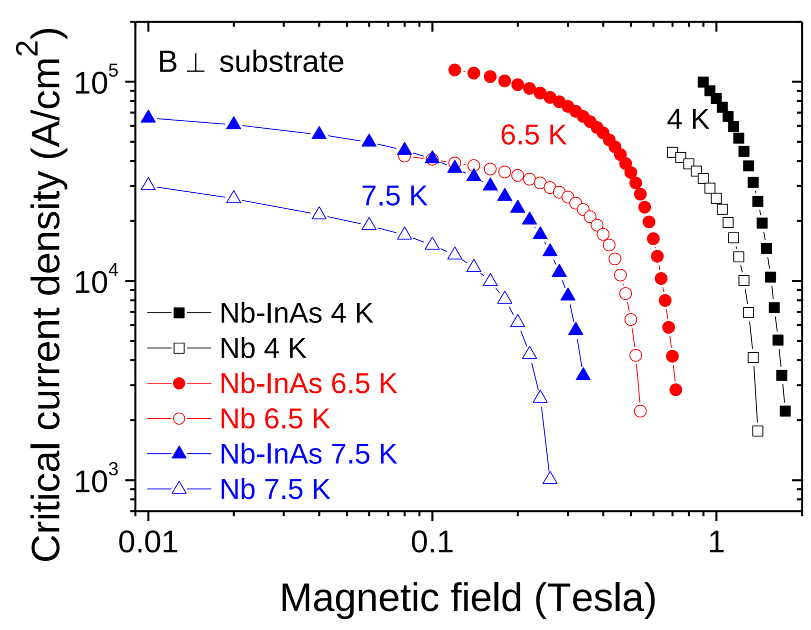
- Higher T_c in Nb-InAs than in Nb for field ⊥ substrate
- But broader transitions in Nb-InAs nanorods

Upper critical field $B_{c2}(T)$ in perpendicular direction

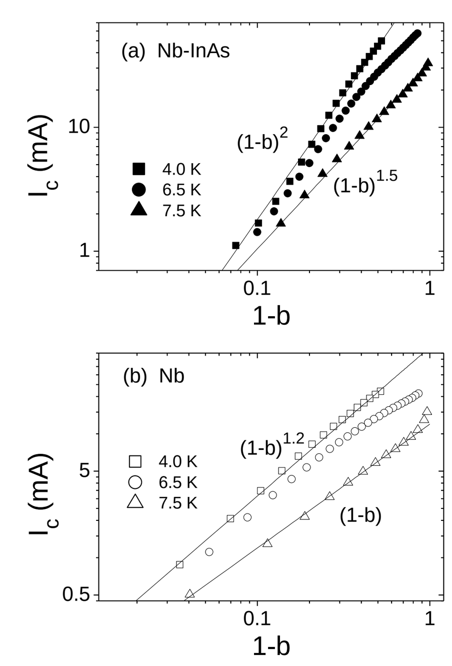


- $B_{c2}(0) \approx 4.5$ T
- Coherence length
  $\xi(0) \approx 8.4$ nm, $\xi(4\text{ K}) \approx 12$ nm
  $\xi(6.5\text{ K}) \approx 17$ nm, $\xi(7.5\text{ K}) \approx 24$ nm
- Nanowire diameter (80 nm) > 2ξ

Critical current density: J_c

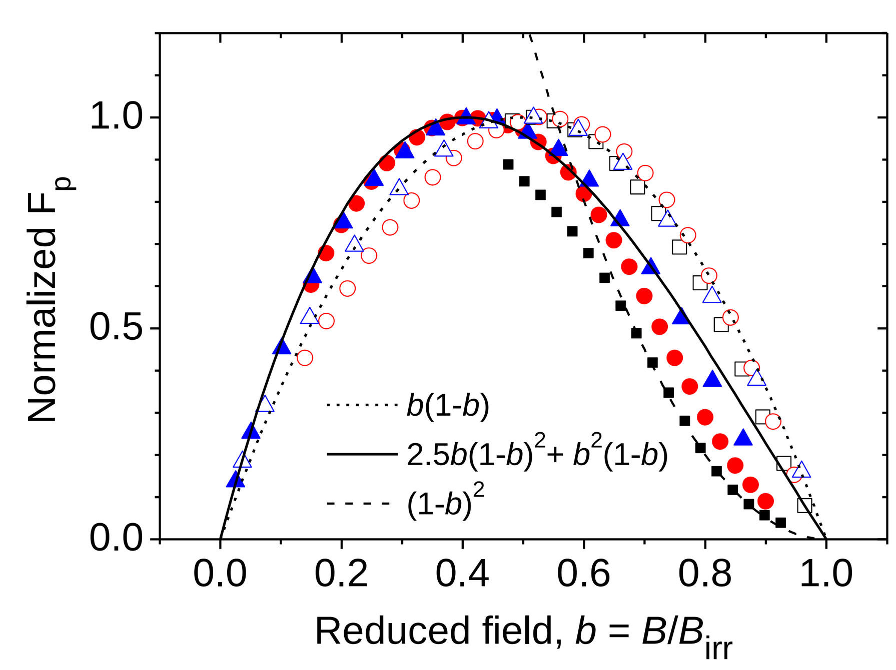


- Enhanced J_c for all T in Nb-InAs for perpendicular fields



- Power-law dependence of the critical currents I_c on (1-b) of (a) Nb-InAs and (b) Nb, where $b = B/B_{irr}$.
- Nb: $I_c \propto (1-b)^{1-1.2}$
- Nb-InAs: $I_c \propto (1-b)^{1.5-2}$

Scaling of pinning force density: F_p



- Point pin
  Flux line spacing > size of pin
- Volume pin
  Flux line spacing < size of pin

- The size to be compared is the diameter d when a magnetic field is applied parallel to the nanorod axis.
- Crossover field B_0 = 0.38 T

Type of interaction	Geometry of pin	Type of center	Pinning function	Maximum position
Core	Volume	Normal	$(1-b)^2$	$b = 0$
		Δκ	$b(1-b)$	$b = 0.5$
	Point	Normal	$b(1-b)^2$	$b = 0.33$
		Δκ	$b^2(1-b)$	$b = 0.67$

Dew-Hughes, Phil. Mag., vol. 30, pp. 293-305, 1974

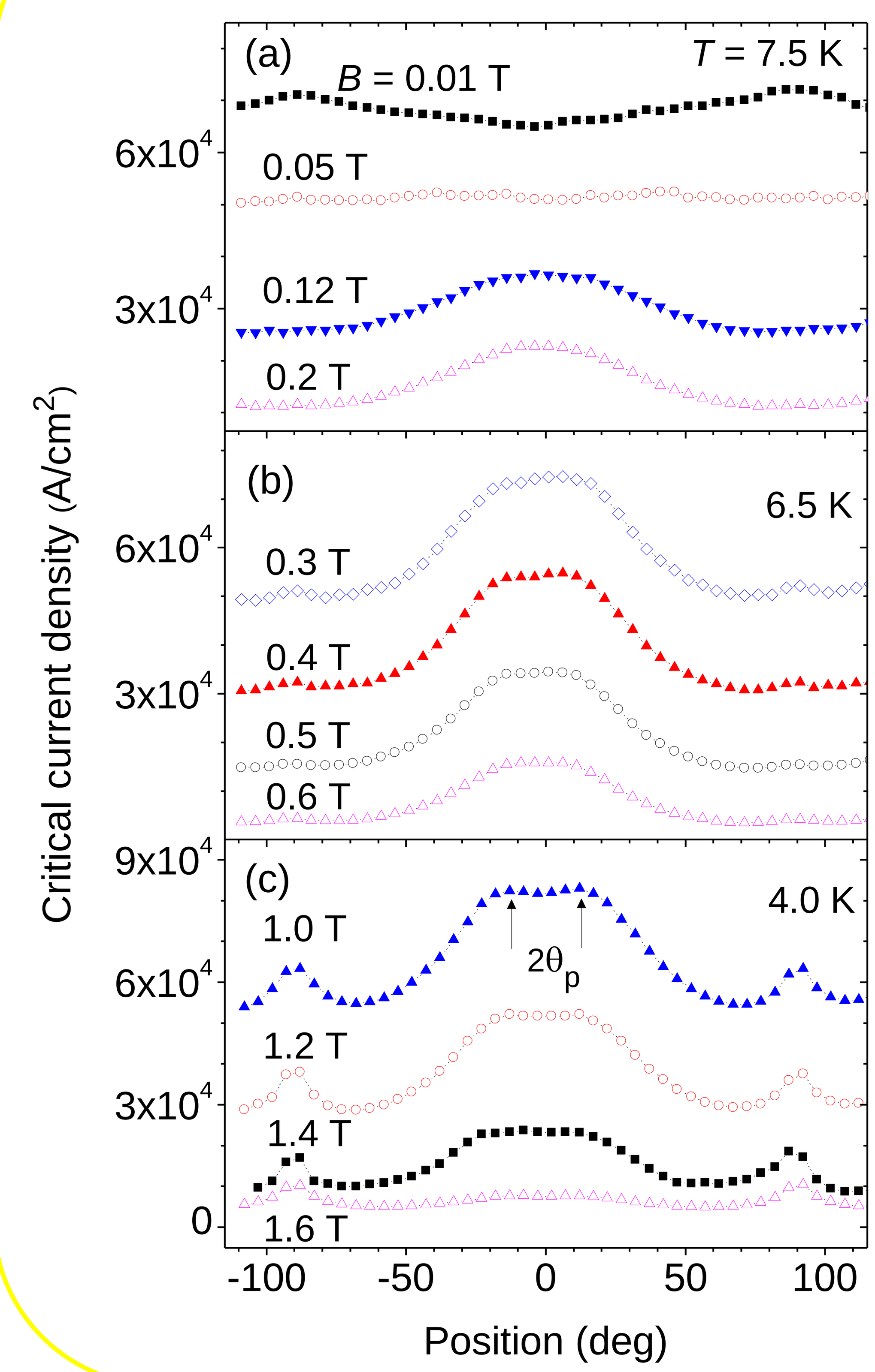
Nb scaling

- Nb results fit well to b(1-b): Δκ volume pinning, but it is unnatural.
- Instead we consider $b(1-b)^2 + b^2(1-b) = b(1-b)$, equal contribution of normal and Δκ point pinning.

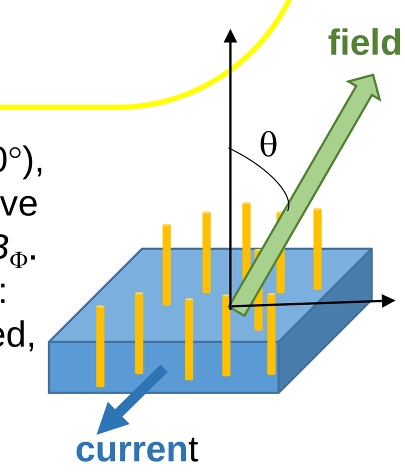
Nb-InAs scaling

- F_p of Nb-InAs at 7.5 K fits well to mixed point pin ($B < B_0$ = 0.38 T): $\mathbf{2.5}b(1-b)^2 + b^2(1-b)$: more of normal point pinning
- $(1-b)^2$ for F_p of Nb-InAs at 4.0 K and b > 0.6 (B > 1.1 T): volume pinning

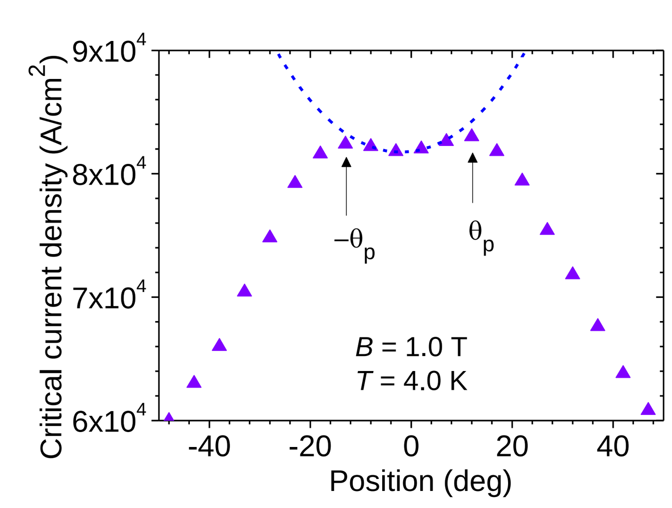
Angular dependence of J_c of Nb-InAs



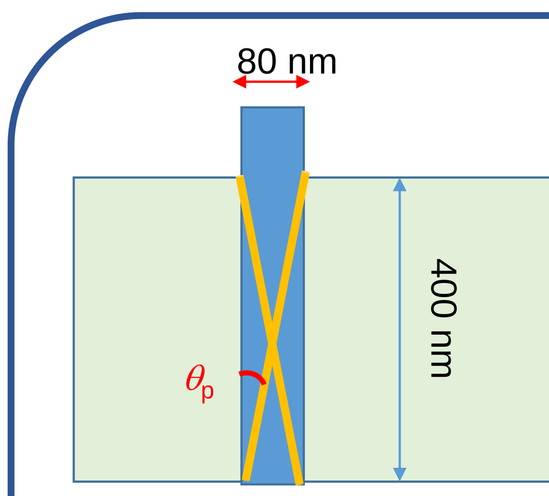
- Between 0.05 T and 1.4 T, $J_c^{\perp}(0°)$ is higher than $J_c^{\parallel}(90°)$, indicating that flux pinning by nanorods is more effective than the surface pinning in the range of $B_\Phi < B < \sim25B_\Phi$.
- Out of the above range, however, $J_c^{\perp}$ is lower than $J_c^{\parallel}$: Below B_Φ, flux motion between linear defects is allowed, above $25B_\Phi$ the flux line density greatly exceeds the nanorod density.



Details of $J_c(0°)$ peak



- Pinned length inside nanorod ~ 1/cosθ (dashed line). When the magnetic field is aligned in the diagonal direction of the embedded part of the nanorod at $\theta = \pm\theta_p$, the length of the pinned flux will be the maximum and J_c will also be at its maximum.
- J_c peak positions are shown by the arrows.
- $\theta_p \approx 13°$



$$\theta_p = \tan^{-1}\left(\frac{80}{400}\right) = 11°$$

- Sketch of pinning of inclined flux lines inside nanorod
- The angle for maximum pinning for 80 nm thick nanowire is 11° for 400 nm thick film.
- Aspect ratio can be an important factor for pinning effectiveness.

Summary

- Feasibility study of semiconducting nanorods for flux pinning centers by measuring transport properties of Nb films on vertically grown InAs nanorods.
- Enhanced T_c, B_{c2}, J_c, and F_p for field applied parallel to the nanorod direction are evidences for effective flux pinning by InAs nanorods even if the nanowire diameter is a few times larger than the coherence length.
- Angular dependence of J_c provides another evidence of flux pinning by InAs nanorods and it also suggests that flux pinning by nanorods is more effective than the surface pinning in the range of $B_\Phi < B < \sim30B_\Phi$.
- Broad J_c plateau with a dip structure at around perpendicular field can be understood in terms of accommodation of inclined flux lines inside the nanorods.