

Quantum oscillations in semiconductor/superconductor hybrid structures

M. Coombs,^{1,*} T. A. J. van Schijndel,^{2,*} Y. Wu,² J. T. Dong,¹ Y. Gul,⁴ J. Choi,³
C. J. Palmström,^{1,2} and G. P. Mazur^{1,5,+}

¹Materials Department, ²Department of Electrical and Computer Engineering, and

³Department of Physics, University of California, Santa Barbara, CA 93106, USA

⁴London Centre for Nanotechnology, University College London, London WC1H 0AH, UK

⁵Department of Materials, University of Oxford, Parks Road, Oxford OX1 3PH, UK

Hybrids of semiconductors and superconductors are the platform of choice for gatemon qubits and Kitaev chains [1]. However, the semiconductor parameters that enter the models of these devices are rarely measured in the hybrid itself: the metal shunts transport, so density, mobility, mass and g -factor are inferred from etched Hall bars or uncapped sister wafers.

Here we resolve this limitation by measuring the semiconductor directly beneath the superconductor through Shubnikov–de Haas (SdH) oscillations: Landau levels are unresolved in the disordered film, so the oscillations originate from the semiconductor subbands alone [2]. We study a 7-nm InAs quantum well beneath a 10-nm $\text{In}_{0.75}\text{Ga}_{0.25}\text{As}$ barrier, capped at 7 K with Al, Sn, V, Nb, Ta or Re, and introduce a Dingle analysis that accounts for the shunt [3].

Remarkably, every metal adds an interface subband absent from the bare well (Fig. 1). Its density falls into two classes that do not follow the work function, $(5.3\text{--}6.5) \times 10^{11} \text{ cm}^{-2}$ beneath the d -band metals and $(1.2\text{--}1.3) \times 10^{12} \text{ cm}^{-2}$ beneath Al and Sn, pointing to Fermi-level pinning at two distinct levels. Importantly, the buried well is unaffected: its cyclotron mass ($0.040\text{--}0.044 m_e$) and $|g| = 4.9 \pm 0.2$, from spin zeros in tilted field, match the uncapped well beneath all six films, and no film shortens its quantum lifetime, while Al and Sn lengthen it. The lifetimes bound the hybridization of the interface subband to $\Gamma \leq 2\text{--}4 \text{ meV}$. Crucially, these are the normal-state parameters that tunnelling spectroscopy renormalizes but cannot access [4], so quantum oscillations emerge as the natural complement of tunnelling spectroscopy in hybrid devices.

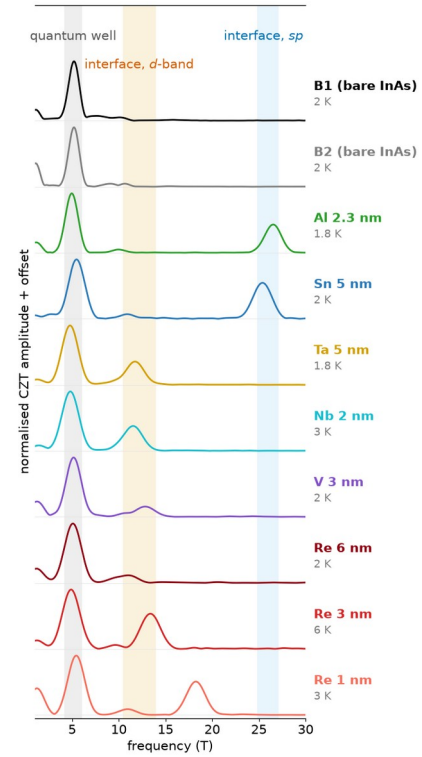


Figure 1. Chirp-z spectra of SdH oscillations of the uncapped wells (B1, B2) and of the well beneath six films. Each metal adds an interface branch next to the quantum-well peak near 5 T.

[1] T. W. Larsen *et al.*, Phys. Rev. Lett. **115**, 127001 (2015); T. Dvir *et al.*, Nature **614**, 445 (2023).

[2] A. M. Zimmerman *et al.*, arXiv:2605.13722 (2026).

[3] M. Coombs *et al.*, arXiv:2609.01593 (2026).

[4] C. Reeg *et al.*, Phys. Rev. B **97**, 165425 (2018); A. E. Antipov *et al.*, Phys. Rev. X **8**, 031041 (2018).

* These authors contributed equally. + Author for correspondence: gmazur@ucsb.edu

Supplementary Information

S1. Samples and measurement. The heterostructure is an $\text{In}_{0.75}\text{Ga}_{0.25}\text{As}$ (10 nm)/ InAs (7 nm)/ $\text{In}_{0.75}\text{Ga}_{0.25}\text{As}$ quantum well grown by molecular-beam epitaxy; B1 and B2 are uncapped references. Al, Sn and V (effusion cell) or Nb, Ta and Re (electron beam) were deposited at 7 K after As-cap desorption in atomic hydrogen, and protected by a nominal 2.5-nm Al layer oxidized in situ before warm-up. Four-terminal resistance was measured on unpatterned material with collinear probes 1 mm apart, up to 14 T at 1.8–20 K, only where the film is normal.

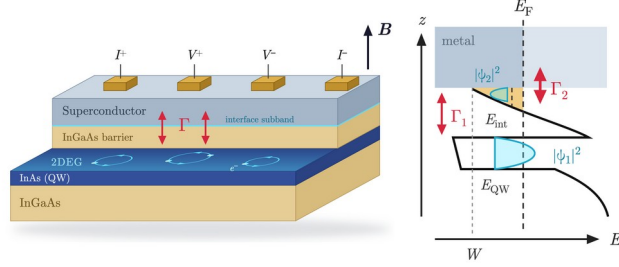


Figure S1. *Left:* heterostructure and four-probe geometry. *Right:* conduction-band profile (not to scale) with the buried-well state $|\psi_1|^2$, the metal-induced interface state $|\psi_2|^2$, their band minima and their coupling rates Γ_1 , Γ_2 to the metal.

S2. Shunt-corrected Dingle analysis. Channels add in conductivity, so beneath a film the measured resistance responds to the oscillatory conductivity of each subband, $\delta R = -(R_s^2/g) \delta\sigma_{xx}$, with $R_s(B)$ the smooth sheet resistance and g a geometric factor. $\delta\sigma_{xx}$ carries the Drude prefactor $P = (\mu_t^2 B^2 - 1)/(1 + \mu_t^2 B^2)^2$ of the transport mobility μ_t , which cancels in the tensor inversion for an uncapped well but not for a shunted one, and produces the non-monotonic envelopes of Fig. S2(e,f). Each branch is therefore fitted to

$$A(B) = A_0 (X/\sinh X) R_s^2(B) |P(B; \mu_t)| \exp[-\pi/(\mu_q B)], \quad (\text{S1})$$

with $X/\sinh X$ the thermal factor at the branch's own mass. The background does not fix μ_t , so the quantum mobility μ_q is quoted as an interval from $\mu_t \rightarrow \infty$ to $\tau_t/\tau_q = 2$, the smallest ratio measured on the uncapped wells. The intervals reproduce to 1–10% across analysis temperatures of 2–6 K, whereas a conventional Dingle plot of the same data moves by factors of 1.5–4.

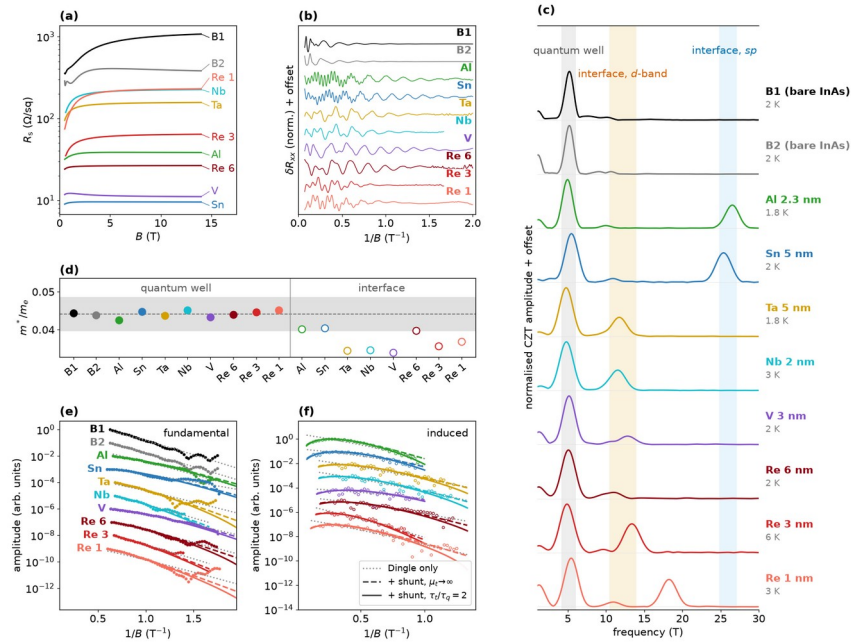


Figure S2. Oscillations of the buried well beneath six films; B1 and B2 are uncapped. (a) Smooth sheet resistance. (b) Background-subtracted oscillations at the lowest normal-state temperature, normalized and offset. (c) Chirp-z spectra of (b). (d) Cyclotron masses of quantum-well (filled) and interface (open) branches; shading, quantum-well mean $\pm 10\%$. (e, f) Amplitudes of the fundamental (e) and interface (f) branches, offset by decades; grey dotted, conventional Dingle fits; coloured dashed, Eq. (S1) in the $\mu_t \rightarrow \infty$ limit; coloured solid, at $\tau_t/\tau_q = 2$.

S3. Spin zeros and coupling bounds. In a tilted field the orbital quantization follows $B \cos \theta$ while the Zeeman energy follows B , so the spin factor vanishes at $|g_{\text{eff}}| m^*/m_e = \cos \theta_z$, independently of the amplitude correction. Every quantum-well branch passes its first spin zero at $\theta_z = 77.8\text{--}79.5^\circ$ (Fig. S3a,b,d), giving $|g_{\text{eff}}| m^*/m_e \approx 0.20 \pm 0.01$ and, with the measured masses, $|g_{\text{eff}}| = 4.9 \pm 0.2$ beneath every film. Escape into the metal adds $2\Gamma/\hbar$ to the Landau-level width, so $\Gamma \leq \hbar/2\tau_q$, giving $\Gamma_{\text{int}} \leq 1.9\text{--}3.8$ meV for the interface subbands (Table S1). For the buried well, subtracting the disorder rate of the uncapped wells, and assuming the film does not reduce it, gives a far tighter bound on Γ_{QW} and induced-gap ceilings well below Δ_0 (Fig. S3f; none for Sn, whose lifetime exceeds both references). Integrating out the superconductor gives a quasiparticle weight $Z = (1 + \Gamma/\Delta_0)^{-1}$ that enhances the mass to m^*_N/Z and interpolates the g -factor, $g_{\text{sub}} = Zg_{\text{Sm}} + (1 - Z)g_m$; for an induced gap of $0.5 \Delta_0$, $Z = 0.54$, which roughly doubles the mass of an interface subband with the measured parameters and suppresses its Zeeman splitting nearly threefold.

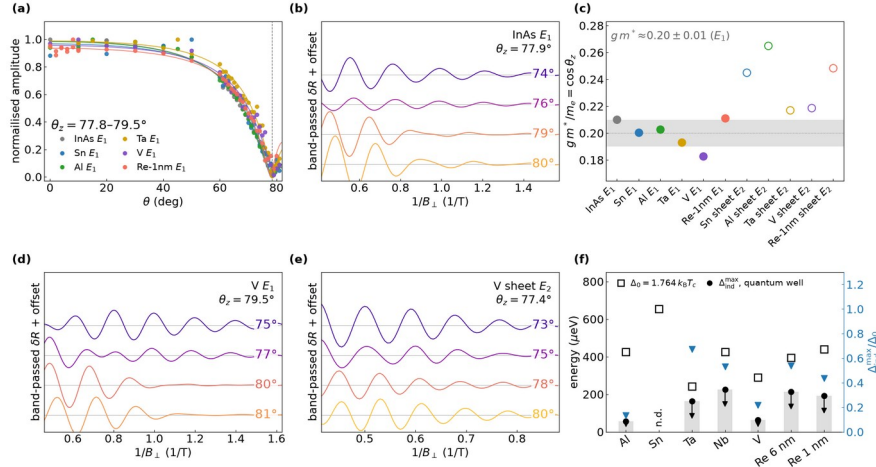


Figure S3. (a) Tilt dependence of the fundamental-branch (E_1) amplitude for the uncapped well and the Sn-, Al-, Ta-, V- and 1-nm-Re-capped samples, normalized to the low-angle value, with damped coincidence fits; all pass their first spin zero at $\theta_z = 77.8\text{--}79.5^\circ$. (b) Band-passed oscillations of the uncapped well either side of $\theta_z = 77.9^\circ$; the inversion identifies the spin zero without a lineshape model. (c) Spin-zero products $|g m^*/m_e| = \cos \theta_z$ for the quantum-well branches (E_1 , filled) and the interface-sheet branches (E_2 , open); dashed line and shading, 0.20 ± 0.01 . (d,e) The same as (b) for the V fundamental (d) and V interface (e) branches. (f) Upper limits on the gap induced in the buried well (circles, bars), parent gaps $\Delta_0 = 1.764 k_B T_c$ (squares) and their ratio (triangles, right axis); n.d., no bound for Sn.

Table S1. Measured subband parameters and coupling bounds. $n = 2eF/\hbar$; μ_q intervals from Eq. (S1) between $\mu_i \rightarrow \infty$ and $\tau_i/\tau_q = 2$; Γ_{max} is $\hbar/2\tau_q$ for interface subbands and the lifetime difference from the uncapped wells for quantum-well branches; $\Delta_{\text{ind}}^{\text{max}}$ follows from the pole of the self-energy with $\Delta_0 = 1.764 k_B T_c$. All coupling entries are upper limits; n.d., not determined. [†]The 3-nm Re interface lifetime assumes $m^* = 0.042 m_e$.

Subband	Film	T_c (K)	F (T)	n (10^{11} cm^{-2})	m^*/m_e	μ_q ($10^3 \text{ cm}^2/\text{Vs}$)	τ_q (ps)	Γ_{max} (meV)	$\Delta_{\text{ind}}^{\text{max}}$ (μeV)
Quantum well	B1 (uncapped)	n/a	5.2	2.5	0.040	9.9	0.23	n/a	n/a
	B2 (uncapped)	n/a	5.2	2.5	0.042	12.1	0.28	n/a	n/a
	Al, 2.3 nm	2.8	5.0	2.4	0.041	10.9–16.0	0.25–0.37	0.18	131
	Sn, 5 nm	4.3	5.5	2.7	0.044	12.2–15.9	0.31–0.40	n.d.	n.d.
	Ta, 5 nm	1.6	4.8	2.3	0.041	8.4–12.3	0.20–0.29	0.56	193
	Nb, 2 nm	2.8	4.8	2.3	0.040	10.2–15.4	0.23–0.35	0.31	195
	V, 3 nm	1.9	5.2	2.5	0.044	9.3–12.6	0.23–0.32	0.28	153
	Re (cryst.), 6 nm	2.6	5.1	2.5	0.043	8.1–10.8	0.20–0.26	0.52	249
	Re (amorph.), 3 nm	5.6	4.9	2.4	n.d.	n.d.	n.d.	n.d.	n.d.
	Re (amorph.), 1 nm	2.9	5.4	2.6	0.042	8.4–12.8	0.20–0.31	0.55	273
Interface	Al, 2.3 nm	2.8	26.5	12.8	0.042	4.3–5.9	0.10–0.14	3.2	412
	Sn, 5 nm	4.3	25.4	12.3	0.035	4.3–5.8	0.09–0.12	3.8	619
	Ta, 5 nm	1.6	11.7	5.7	0.037	6.5–9.5	0.14–0.20	2.4	238
	Nb, 2 nm	2.8	11.6	5.6	0.036	6.0–9.2	0.12–0.19	2.7	407
	V, 3 nm	1.9	12.4	6.0	0.041	n.d.	n.d.	n.d.	n.d.
	Re (cryst.), 6 nm	2.6	11.0	5.3	0.042	7.1–9.2	0.17–0.22	1.9	368
	Re (amorph.), 3 nm	5.6	13.4	6.5	0.042 [†]	5.0–6.8	0.12–0.16	2.7	739
	Re (amorph.), 1 nm	2.9	18.3	8.8	0.037	5.0–7.5	0.11–0.16	3.1	424