

I ACHIEVEMENTS

NTU Achieves First Direct Measurement of Carrier Transfer in 2D Transistors

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An innovative platform technology recently developed at NTU has set a new benchmark for contact metrology in next-generation semiconductor devices.

A research team at National Taiwan University (NTU), led by Distinguished Professor Ya-Ping Chiu of the Department of Physics, has innovated an operando cross-sectional scanning tunneling microscopy and spectroscopy platform (operando XSTM/STS). This entirely new metrology capability enables the direct measurement of carrier injection at metal/semiconductor contact edges while a transistor is under actual operating conditions. Their study, "Directly probing the carrier transfer length in 2D-material transistors," was published in *Nature* on July 1, 2026.

As semiconductor devices scale toward and beyond the 1 nm technology node, two-dimensional (2D) semiconductors have emerged as promising candidates for developing future logic technologies. Continued transistor scaling depends not only on shortening the channel length but also on shrinking the metal contact region. The carrier transfer length—the effective spatial extent over which carriers are injected from a metal electrode into the semiconductor channel—governs contact resistance and thus is a key indicator of scaling viability. Until now, this parameter has been accessible only through indirect methods based on theoretical models, which break down in 2D semiconductor systems.

Building on nearly two decades of in-house cross-sectional STM expertise, the NTU team integrated an *in situ* biasing and gate-control system into an ultrahigh-vacuum platform, enabling synchronized spectroscopy while the transistor operates under source-drain and gate voltages. The team successfully cleaved Bi-contacted monolayer MoS₂ transistors under ultrahigh-vacuum conditions, exposing a clean cross section of the metal contact and semiconductor channel. By mapping shifts in the MoS₂ conduction-band edge along the contact interface, the researchers directly measured a carrier transfer length of approximately 2.0 nm—more than four times shorter than the 9.25 nm value obtained using the conventional transfer-length method (TLM) on the same devices. The method was also validated for HfO₂-gated MoS₂, *p*-type PdSb/WSe₂, and silicon-on-insulator (SOI) devices, demonstrating its applicability across both 2D and conventional semiconductor platforms.



Operando cross-sectional scanning tunneling microscopy (operando XSTM), developed at NTU, enables the first direct measurement of carrier transfer length at the contact edge of operating 2D semiconductor transistors with atomic-scale spatial resolution. *Nature* 655, 350–356 (2026).



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These results establish operando XSTM/STS as the first experimental method capable of directly measuring carrier transfer length in operating transistors with sub-nanometer spatial resolution, closing a critical gap in semiconductor contact metrology. The platform will provide the semiconductor research community with a direct, model-free tool for benchmarking and optimizing contact engineering across diverse material systems. It is poised to become a valuable resource for guiding contact design and accelerating process integration as the industry advances toward angstrom-scale devices.

The study was a collaboration between the research team at National Taiwan University and research groups at the National University of Singapore and National Taiwan Normal University.