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Title

Coherent scanning tunneling microscopy.

Permalink

<https://escholarship.org/uc/item/4771j4w1>

Journal

Science (New York, N.Y.), 367(6476)

ISSN

1095-9203

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Publication Date

2020-01-24

NANOPHOTONICS

Coherent scanning tunneling microscopy

Ultrafast phase-stabilized optical pulses add temporal resolution to high spatial resolution

By **Clarice D. Aiello**

The ultimate goal of any nanotechnology is to resolve and control elementary processes in matter. In general, although many spectroscopies can achieve high temporal resolution and many microscopies can achieve high

spatial resolution, achieving both is difficult. On page 411 of this issue, Garg and Kern (1) improve the limits of concomitant spatial and temporal resolutions by combining scanning tunneling microscopy (STM) (2) with an ingenious phase-locking train of ultrafast optical pulses. The authors go on to demonstrate that their instrument can deconvolve femtosecond electron dynamics with nanoscale resolution. These feats are only made more interesting because the phase-locking scheme enables an imprint of the laser's (coherent) phase onto the tunneling electrons. This demonstration of "light-wave electronics" at atomic scales is unprecedented.

Coherence and coherent control have widely varying meanings across fields, so it is important to be specific in how the terms are meant in these studies (3). Electron tunneling through a barrier is not a process that physicists usually think of as "coherent." For example, when a voltage is applied onto a STM tip near a metal surface, the stimulated tunneling current lacks coherence because electrons are affected by the randomly evolving phase of the applied voltage.

By contrast, the experiments of Garg and Kern exhibit coherent tunneling, defined here as an electronic current with a well-defined phase at the nanoscale. The carrier-envelope phase φ_{CEP} is defined as the phase between the carrier wave and the maximum of its intensity envelope (4). The approach to control electronics with CEP-stabilized optical pulses is known as light-wave electronics (5). When a STM tip is excited with CEP-stabilized pulses, a very strong electric field of $\sim 1 \text{ V/\AA}$ is created that can lower the tunneling barrier (see the figure). The induced tunneling current will

be coherent, provided that the pulses' phase is indeed stable for the duration of the tunneling process (which is estimated to be on the femtosecond time scale).

In such cases, the tunneling current intensity (I) is predicted to oscillate with φ_{CEP} , that is, I is proportional to $\exp(i\varphi_{\text{CEP}})$. It is in this sense that the pulses' phase is imprinted onto

essential ingredient of nanoelectronics, namely, control over atomic-level currents. The other essential ingredient is manipulation speed. Such optical pulses, which are on the several-femtosecond scale, correspond to frequencies of hundreds of terahertz, which compares favorably to current electronics that operate in the gigahertz to terahertz regimes (6).

Finally, Garg and Kern use the same experimental method to study fast carrier-decay dynamics in nanostructures. A STM tip was placed in the close vicinity of gold nanorods and excited by CEP-stabilized optical pulses in a type of pump-probe configuration. The tunneling current varies with the delay between pulse and probe pulses with a dominant frequency component matching a plasmon resonance in the nanorods. This observation suggests that the laser is effectively exciting a plasmon resonance that decays within a time scale ($\sim 40 \text{ fs}$) that was well resolved by the method.

More broadly, the experimental tool kit advanced here can be put to use to investigate charge-transport phenomena in nanostructures and in single molecules adsorbed onto a surface, including molecules of biological relevance. The reported experiments should encourage research into unexplored avenues. For example, manipulating the spins of the tunneling electrons with similar techniques would allow investigations of the chiral-induced spin selectivity effect (7) at the single-molecule level. Additionally, quantum computing protocols might harness the coherent tunneling phase. In any case, Garg and Kern's present experimental tour de force should already entice the reader to be on the lookout for nanomicroscopy and nanoelectronics techniques that

use the combined power of STMs and CEP-stabilized ultrafast optical pulses. ■

REFERENCES AND NOTES

1. M. Garg, K. Kern, *Science* **367**, 411 (2020).
2. B. Voigtländer, *Scanning Probe Microscopy: Atomic Force Microscopy and Scanning Tunneling Microscopy* (NanoScience and Technology Series, Springer, 2015).
3. T. Baumgratz et al., *Phys. Rev. Lett.* **113**, 140401 (2014).
4. K. Yoshioko et al., *Nat. Photonics* **10**, 762 (2016).
5. E. Goulielmakis et al., *Science* **317**, 769 (2007).
6. X. Mei et al., *IEEE Electron Device Lett.* **36**, 327 (2015).
7. R. Naaman, D. H. Waldeck, *J. Phys. Chem. Lett.* **3**, 2178 (2012).

10.1126/science.aba0714

Coherently through the barrier

Garg and Kern irradiated a scanning tunneling microscope tip with phase-stabilized femtosecond optical pulses. The resulting strong electric fields produce in-phase electrons (e) whose atomic-scale flux can be tuned within the same time frame. E_F , Fermi energy.

Photon-promoted tunneling

Low fluxes of femtosecond pulses promote the tunneling of electrons by exciting them to higher energy states. Tunneling electrons are not in phase.

Field-induced tunneling

High fluxes of femtosecond pulses with the same carrier-envelope phase (CEP) φ_{CEP} promote tunneling by creating a high electric field that changes the shape and lowers the barrier. Tunneling electrons are in phase, and the current intensity I is proportional to the experimentally tunable CEP.

the tunneling electrons. In the experimental setup of Garg and Kern, φ_{CEP} could be chosen and tuned at will. This capability, which was enabled by the CEP feed-forward lock they developed, will be of relevance for a broad class of instrument builders.

As a proof-of-principle experiment, a CEP-stabilized train of ultrafast optical pulses was impinged on a STM tip near a gold surface. By varying the CEP, Garg and Kern could indeed measure modulations of tunneling current intensity. This demonstrated one es-

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Science **367** (6476), 368.

DOI: 10.1126/science.aba0714

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