Atomically resolved terahertz scanning tunneling spectroscopy as a tool for exploring ultrafast dynamics new materials

S. E. Ammerman[1], V. Jelic[1], Y. Wei[1], V. N. Breslin[1], M. Hassan[1], N. Everett[1], S. Lee[1], S. Adams[1], Q. Sun[2], C. Pignedoli[2], P. Ruffieux[2], R. Fasel[2,3], and <u>T. L. Cocker[1]</u>

[1]Michigan State University, East Lansing, United States
[2]Empa, Dübendorf, Switzerland
[3]University of Bern, Bern, Switzerland

Lightwave-driven scanning tunneling microscopy achieves exquisite spatio-temporal resolution through coherent control of tunnel currents with the oscillating field of a single-cycle light pulse. It was first demonstrated at terahertz frequencies [1], which are particularly well suited to such strong-field control [2,3]. Terahertz scanning tunneling microscopy (THz-STM) has subsequently been used to resolve the picosecond motion of single molecules [4] and extreme tunnel currents through single silicon atoms [5], among other exciting recent results [3]. Thanks to its combination of ultrafast temporal resolution with atomic spatial resolution, THz-STM promises further breakthroughs, especially as a tool for exploring new materials. Yet, its unique view also necessitates a deep understanding of how THz-STM measurements relate to the underlying physics of the system, as it may not be visible to any other experimental technique. Here, we establish an experimental [6] and theoretical [7] framework for atomically resolved terahertz scanning tunneling spectroscopy, which we believe will be a key modality for future studies of complex dynamics such as photoinduced phase transitions.

References

[1] T. L. Cocker, V. Jelic, M. Gupta, S. J. Molesky, J. A. J. Burgess, G. De Los Reyes, L. V. Titova, Y. Y. Tsui, M. R. Freeman and F. A. Hegmann, Nature Photonics **7**, 620 (2013).

[2] J. Lloyd-Hughes *et al*. J. Phys.: Condens. Matter **33**, 353001 (2021).

[3] T. L. Cocker, V. Jelic, R. Hillenbrand and F. A. Hegmann, Nature Photonics **15**, 558 (2021).

[4] T. L. Cocker, D. Peller, P. Yu, J. Repp and R. Huber, Nature **539**, 263 (2016).

[5] V. Jelic, K. Iwaszczuk, P. H. Nguyen, C. Rathje, G. J. Hornig, H. M. Sharum, J. R. Hoffman, M. R. Freeman and F. A. Hegmann, Nature Physics **13**, 591 (2017).

[6] S. E. Ammerman, V. Jelic, Y. Wei, V. N. Breslin, M. Hassan, N. Everett, S. Lee, Q. Sun, C. Pignedoli, P. Ruffieux, R. Fasel and T. L. Cocker, In press.

[7] S. E. Ammerman, Y. Wei, N. Everett, V. Jelic and T. L. Cocker, Submitted.