Optical field-driven ultrafast electron control inside of graphene and at the surface of metal needle tips

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With femtosecond laser pulses, electrons can be driven on ultrafast timescales. If these laser pulses are just two optical cycles long (roughly 5 fs pulse duration at 800 nm center wavelength, 1 fs = 10^{-15} sec), it matters how the exact optical field looks like within the laser pulse envelope – but this optical field can be well controlled these days in so-called phase-stable laser pulses.

This talk will give an overview of our work circling around controlling electrons on sub-femtosecond time scales with phase-controlled laser pulses. After a brief introduction to these laser pulses, the first part of the talk will focus on strongly driven electrons inside of graphene. We could show that electrons undergo coherent coupled intraband motion and interband transitions. More specifically, we could demonstrate subsequent coherent Landau-Zener transitions, allowing us to realize Landau-Zener-Stückelberg-Majorana interferometry with electrons inside of graphene. Based on this physics, we could demonstrate a record-fast current switch, with a turn-on time of around 1fs, leading to real charge carrier generation [1]. Just recently, we also gained deep insights into how the graphene-gold interface can be used to read out virtual charge carriers. Based on these insight, we could demonstrate a logic gate potentially providing petahertz bandwidths [2].

The focus of the second part of the talk will be on strongfield physics at the surface of metal needle tips. Here we could demonstrate that we can control photo-emitted electrons with the help of phase-controlled laser pulses fully coherently. We observe all hallmarks of strongfield physics, now at the surface of a solid [3]. With more complex two-color laser fields, we could fully reconstruct the attosecond-fast emission dynamics (1 as = 10^{-18} sec). In particular, we find a tunneling time of 710 ± 30 attosec, i.e., we can now trace electron emission dynamics from solids with attosecond time resolution [4].

[1] Higuchi et al., Nature **550**, 224 (2017); Heide et al., PRL **121**, 207401 (2018); Heide et al., Nat. Phot. **14**, 219 (2019); Heide et al. NanoLett. **21**, 9403 (2021); Heide et al., PRA **104**, 023103 (2021)

[2] Boolakee et al., Nature **605**, 251 (2022);

[3] Krüger et al., Nature **475**, 78 (2011); Krüger et al., J. Phys. B **51**, 172001 (2018);

[4] Dienstbier et al., manuscript submitted

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